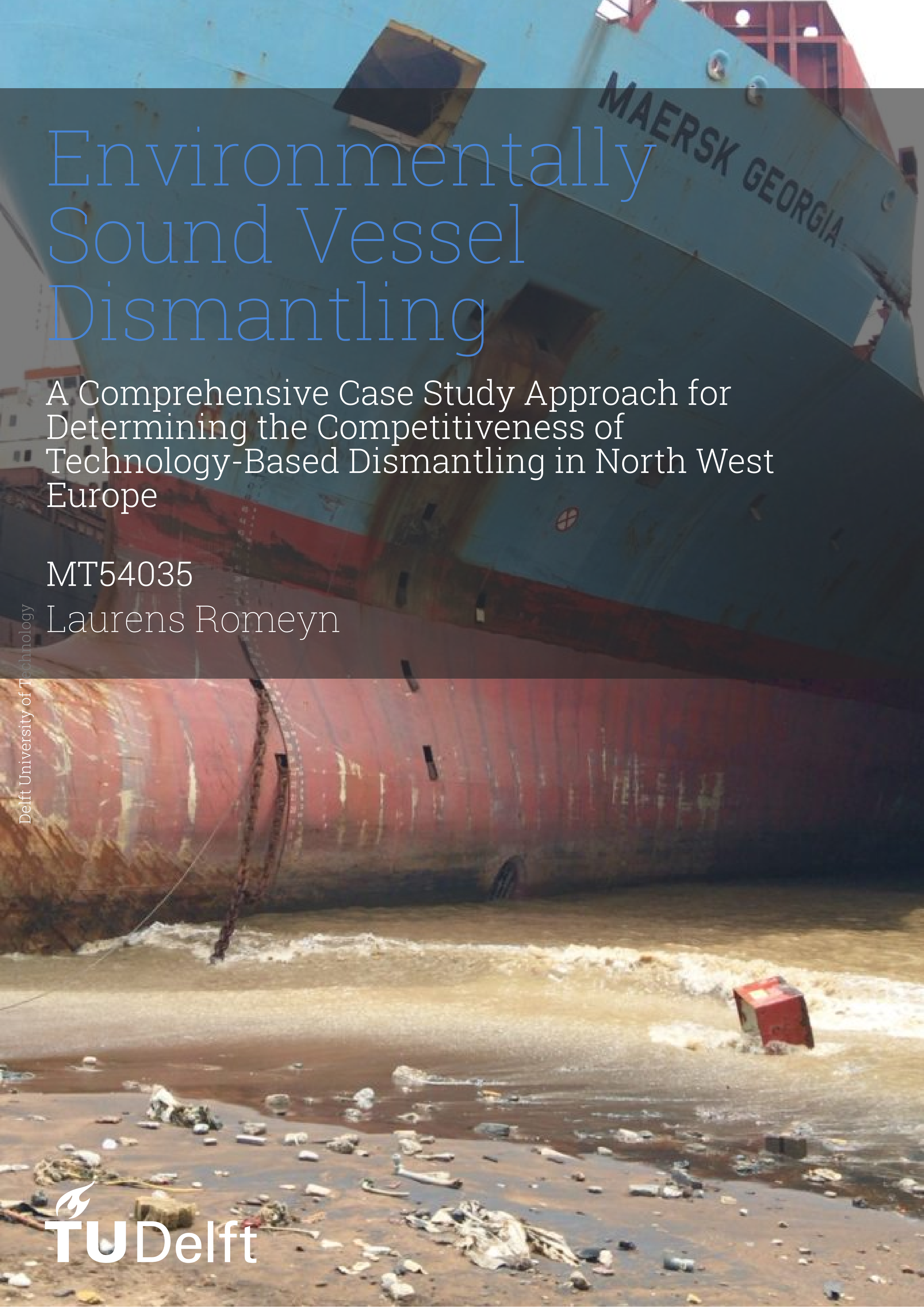


# Environmentally Sound Vessel Dismantling

## A Comprehensive Case Study Approach for Determining the Competitiveness of Technology-Based Dismantling in North West Europe

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Delft University of Technology

Thesis for the degree of MSc in Marine Technology in the specialisations of Maritime Operations and Management & Ship Design

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## A Comprehensive Case Study Approach for Determining the Competitiveness of Technology-Based Dismantling in North West Europe

by

Laurens Romeyn

This thesis (MT.23/24.006.M) is classified as confidential in accordance with the general conditions for projects performed by the TU Delft.

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# Abstract

A vessel's life cycle consists of the design, construction, operation, and scrapping of the vessel. Current scrapping practices often happen in South Asia and Turkey, where adverse impacts on the environment and people's health and safety manifest itself. These negative impacts fuel the growing global criticism on the vessel dismantling industry. Academic research on this topic has mainly been focused on qualitative research of the extent of the impact, while minimal research is dedicated to the understanding of alternative dismantling processes, which could improve industry standards. Several factors including regulations and a changing market dynamic of the steel industry enabled new parties to potential market entry of the vessel dismantling business. The new parties aim to include high standards of waste management and no social harm in their business, by relying on a technology driven dismantling process. These circumstances and alternative dismantling concepts in developing countries justify an investigation on the level of competitiveness, compared to the conventional labour-based dismantling concepts of South Asia and Turkey. Therefore, the main question of this research is:

**What is the level of competitiveness of technology-based, environmentally sound vessel dismantling located in North Western Europe?**

In order to create an understanding of the level of competitiveness of technology-based dismantling, a thorough analysis of the underlying problems causing global criticism had to be performed. Through literary research the historical developments and drivers of the industry have been identified in chapter 2. The adverse impact on coastal ecology and involved occupational hazards and child labour is proven in section 2.2. Following this, regulatory frameworks were drawn up to improve the workings of end of life vessel management. This resulted in more reliance on developing economies adhering to poor enforcing regulation due to non-uniform ratification of the frameworks, as discussed in section 2.2.2. Earlier research on measurement models for sustainability within the dismantling industry was mainly focused on high over managerial and social practices, instead of the dismantling process from an operational-economic perspective.

The identified knowledge gaps required for answering the main question formed the basis of the scope structuring and research methodologies. For the research methodology discussed in section 3, goal oriented identification of the best fitting method is maintained. The first area of interest for answering the main question came down to selecting and valuing the most potent feedstock for the designated area. The commercial segments and sizes are based on data analysis and holistic data set enlargement. Thereafter, selecting an adequate method for quantifying all material streams of vessels is of importance to create an understanding of the material flows and economic return of the dismantling process. Subsequently, technology-based dismantling could be investigated from an operational perspective. From the understanding of the operational requirements, the link could be made to the required investments and operational expenses. The ecological and social impact required a quantification method that would allow for inclusion in the economic performance of technology-based dismantling. By doing this, a single unit parameter can be used for answering the main question. An overview of all relevant added values and costs, impacts and streams is presented in a sustainable value stream map.

Finally, a case study was selected representing technology-based dismantling in the simulation performed. The concept which matched the scope of this research best is *Circular Maritime Technology*. From the simulation and calculations performed in accordance with the selected methodologies could be concluded that there are both opportunities and challenges for technology-based dismantling concepts in North West Europe. Matching the pricing level of Turkey is found to be economical viable, whilst competing with South Asia requires a level of true pricing allocation in the economic value. For operational viability, minimising the turnaround time of vessels is key for spreading the high investments over enough earnings. Adhering to the right pricing level for vessel acquisition and steel sales is key. Especially in the current phase with the absence of incentives and taxation frameworks promoting sustainable vessel dismantling.

# Contents

# 1 Introduction

Vessels undergo a life cycle consisting of three main elements; construction, operation, and scrapping. In economical terms these life segments comprise of an investment to construct the asset, an operation where the asset generates revenue to justify the investment, and lastly selling the asset for scrapping, because it is amortised and more expensive to keep in operation than it generates upside. In general this is a responsible life cycle, as the scrapping of the vessels implies a certain market recyclability. Nonetheless, current shipbreaking practices consist of elements resulting in a huge negative impact on the environment and people's health and safety. Furthermore, several regulatory frameworks combined with social pressure push shipowners towards including sustainable scrapping in their operational plan. However, an attractive dismantling alternative that both effectively counteracts negative externalities and is financially competitive for shipowners and economically feasible for the dismantling operator has not yet been commercialised.

Besides the global criticism related to the socio-environmental effect of conventional scrapping processes, the world is currently undergoing a behavioural transition where levels of recycling are maximised, in order to decrease the global greenhouse gas [GHG] emissions and virgin material usage. One of the largest polluters is the construction industry, with in particular the cement and steel industry (Gates, 2021). European steel factories are under pressure to decarbonise as quickly as possible. In the past 40 years there has been a 50% reduction in energy consumption in the steel industry in Europe, mainly driven by process improvements, material efficiency and recycling scrap usage (*Resource Efficiency for the European steel industry*, 2011). In addition, many other toxic emissions have been found in vicinity of steel factories, causing health problems ("Directe relatie tussen uitstoot Tata Steel en hinder en kans op ziekte", 2023). The previous reductions are amplified due to a diversity of legislative frameworks pushing towards more accountability for emitted GHG, and other toxic particles. The approach of one of the frameworks aims to include all company emissions, including indirect emissions, into a three-part scope (Deloitte, n.d.). The publication of the entire emission chain, and potential penalisation, results in industrial greenification support. Within the production chain, this emission accountability creates downstream manufacturers' support for the development and implementation of less environmentally pressing production methods of their feedstock.

Various routes exist for the production of steel, which require different inputs [raw materials such as coal and virgin ore, or scrap metal], but more importantly they have different ecological footprints. For steel producers to keep up with the growing demand of steel, while mandating regulation and mitigating additional costs associated with their current emission behaviour, Electric Arc Furnaces [EAF] seem like a solution, with a proven technology selection and improving economics (N. Mikelis, 2019). One of the technological prerequisites of using EAF, compared to the classically used Basic Oxygen Furnaces [BOF] steel production, is an increment in the share of scrap steel used for the production of new steel. The difference in production method and feedstock of the two production methods is identified by figure 1.1. The amount of virgin ore and coke diminishes, while the amount of scrap steel increases significantly. In terms of $CO_2$ per tonnes of crude steel [tcs] production, the difference between the production methods is significant - in favour of EAF (Quader et al., 2015). However, even with the technological possibility for further reducing energy usage and negative health impact, the realisation may be hampered by the availability of scrap steel in general, and clean high-quality scrap steel in particular.

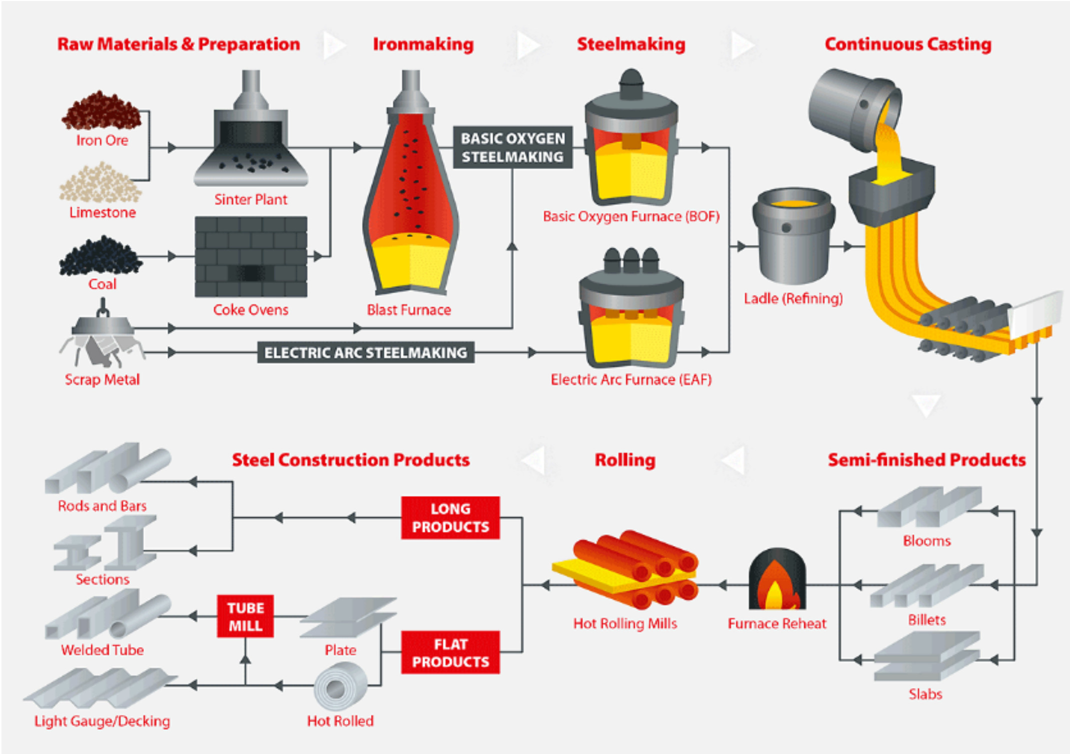



**Figure 1.1:** Steel making production paths

There are two elements of importance which indicate that success can be achieved for this supply chain bottleneck through the vessel dismantling industry. First of all, shipbuilders use high quality steel and most of the lightweight of a vessel consists of steel. Dismantling vessels locally would imply regionally sourced, high quality feedstock for steel manufacturers. Secondly, the steel recycling infrastructure is present in North West Europe [1], but is currently mainly focused on the provision of the Turkish EAF-using steel industry (Schnitzer and Willeke, 2021). Furthermore, the export amount of scrap steel towards Turkey has increased heavily over the past years, as supported by figure 1.2 displaying the annual differences between 2020 and 2021. Moreover, in the EU and Turkey a year-on-year increment in the percentage of recycled steel used is visible [table 1.1], as derived from (Schnitzer and Willeke, 2022). This implies that, with a commercially attractive dismantling concept, dismantling vessels can provide the solution for the anticipated shortage of high-quality scrap steel caused by an increasing demand. Also, an environmentally sound technology-based dismantling located in developed countries can theoretically break the shipbreaking labour conditions and associated environmental impact of the conventional scrapping processes.

**Table 1.1:** Ratio recycled steel versus crude steel

| | **2018** | **2019** | **2020** | **2021** | **2022** |
|---|---|---|---|---|---|
| **EU - 28/27 %** | 54.4 | 55.0 | 57.0 | 57.8 | 58.2 |
| **Turkey %** | 83.9 | 82.8 | 84.1 | 86.1 | 86.3 |
| **Global %** | 82.8 | 83.0 | 82.6 | 81.6 | 86.6 |

[1] Based on the EU-28 import/export position, on global scale

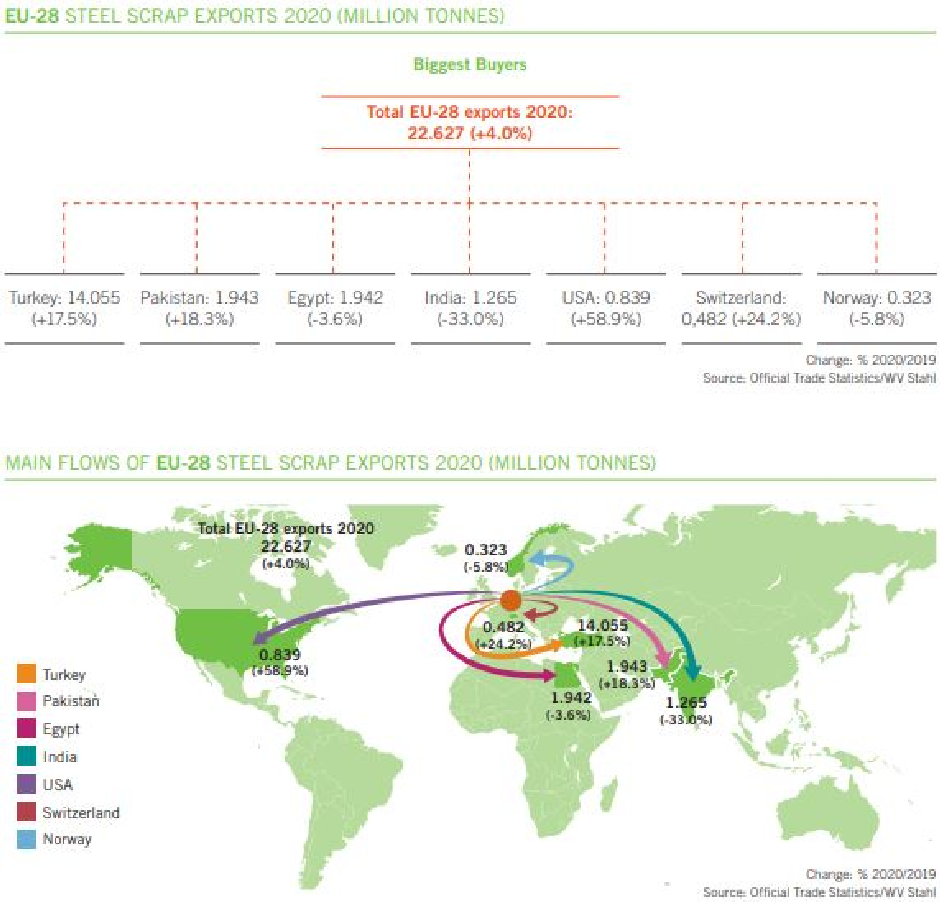



**Figure 1.2:** EU scrap steel market dynamics (Schnitzer and Willeke, 2021)

In order to fulfil this demand for scrap steel while complying with the sustainability frameworks and elevated labour costs established for shipbreaking and waste management, the dismantling process must be reevaluated. For various industries, technologies have been developed to cut large metal structures, re- or upcycle ferrous, non-ferrous as well as organic and inorganic materials that can be found on ocean-going vessels. Besides externalities, another important reason for understanding circular scrapping concepts comes from the shipbuilding industry. Both the processes as well as the engineering feasibility boundaries are relevant to incorporate scrapping practices in sustainable designs and construction processes of vessels. Shipbuilders, especially the ones located in North West Europe, have the ambition to become frontrunner in offering cradle-to-cradle products and addressing circularity within their business (“Values | Damen”, 2021).

The described criticism on the impact of conventional dismantling processes and market trends including anticipated shortage of scrap steel, argue from externalities a justification for the investigation of alternative dismantling. Several scenarios have been evaluated, where the technology-based dismantling concept of *Circular Maritime Technology* has been taken as case study for the process analysis and simulation. This research provides documentation for the level of competitiveness of technology-based dismantling, with substantiations on the findings from the classic economical business model, process analysis, and the effect of ecological and social aspects on technology-based dismantling, answering the main question:

**What is the level of competitiveness of technology-based, environmentally sound vessel dismantling located in North West Europe?**

The scope of this research comprises of the entire supply chain from acquisition to steel manufacturing. In order to substantiate the answer of the main question in relation to this scope, several subjects of interest must be investigated. The sub-questions relevant for this research question are:

1. What are the drivers and workings of the dismantling industry, and what are the adverse consequences of conventional practices?
2. What is the most suitable fleet segment for vessel dismantling in the designated region, and how are these segments valued at end of life?
3. What material streams constitute the selected fleet segments?
4. What are the key operational-economic parameters for technology-based dismantling?
5. What is the ecological, social and economic impact of technology-based dismantling?
6. How does technology-based vessel dismantling compare to the conventional practices from a single unit perspective?
7. What is the effect of potential operational and market deviations on the economic viability of technology-based vessel dismantling?

From the results of this research can be concluded that technology-based dismantling offers an economically viable alternative to the existing methodology and end of life pricing level of Turkish conventional practices. However, in comparison to South Asian practices, this research indicates that the economic pricing level cannot be matched viably. Only by means of allocating [some] of the identified ecological and social costs omitted through technology-based dismantling, a competitive landscape arises. Since this research identifies economic and financial incentives to be dominant factors in end of life vessel management, a tangible bridge that needs to be crossed for an equal level playing field to be established is provided. This research has been performed for the *TU Delft* with the collaboration of *Damen Shipyard Group* and *Enviu*.

# 2
# Problem Analysis

The goal of the problem analysis is to investigate the necessity of a feasible, sustainable ship dismantling concept. The basis of this investigation is identifying the drivers and workings of the conventional dismantling methods, and what negative impacts follow from this. For establishing a structure, the market principle of shipbreaking is used. The basic market principle emanates from the economical principle of supply and demand (Juan Ignacio Alcaidea, 2016). The problem analysis will cover the main parameters within this market principle, and evaluate the effect of technology-based dismantling concepts in the designated area. Through this potential opportunities, challenges and copings of a sustainable technology-based dismantling concept can be identified. Also, the current research on requirements and practices of alternative dismantling processes will be covered.

The parameters that change with a more sustainable dismantling concept are international regulation, market demand of [non-]ferrous products, relevant scrapping costs, and environmental impact regulations. Besides the macro-economical drivers of vessel scrapping, the shipbreaking process itself underwent developments over time as well. The structure maintained for the problem analysis starts with the practical developments of vessel scrapping methodologies, followed by the [in]direct effect of developments in the macro-economic drivers forming the basis of the supply and demand mechanism.

The first step is to relate the shipbreaking principle parameters to key words for establishing a literary collection used to investigate the drivers, workings and adverse consequences of conventional dismantling processes. Besides parameter specific key words, general key words have been used as well. The main categories of key words consist of the workings of the conventional dismantling industry, alternative dismantling processes, the ecological and social impact of the conventional dismantling process, and regulatory frameworks with respect to vessel dismantling. The following keywords have been used for gathering academic literature on shipbreaking practices, as well as possible relatable industries: *green recycling*, *shipbreaking*, *life cycle assessment*, *pollution*, *hazardous waste*, *dismantling*, *ecological indicators*, *environmental indicators*, *the Hong Kong convention*, *steel production*, *child labour* and *upcycling*. Table 2.1 relates the key words [or combinations] to each main category.

**Table 2.1:** Literature research key word structure

| | Conventional dismantling industry | Alternative dismantling industry | Ecological and social impact | Regulatory frameworks |
|---|---|---|---|---|
| Green recycling | | X | X | |
| Shipbreaking | X | X | X | X |
| Life cycle assessment | X | X | X | |
| Pollution | X | | X | X |
| Hazardous waste | X | | X | X |
| Dismantling | X | X | X | |
| Ecological indicators | | | X | |
| Environmental indicators | | | X | |
| Hong Kong convention | X | | X | X |
| Steel production | X | X | X | |
| Child labour | | | X | X |
| Upcycling | | X | X | |

Since limited research is dedicated to the vessel dismantling industry, a structural approach for determining the relevancy of papers is adhered to. The decision-making structure followed consists of:

1. The title and journal of the papers in relation to the problem analysis
2. The abstract and conclusion of the papers in relation to the problem analysis

This resulted in a total of 46 relevant academic papers, where recurring journals include *Journal of Cleaner Production*, *Resources, Conservation & Recycling*, *Ocean Engineering* and *Marine Pollution Bulletin*. In section 3.1 additional keywords will be itemised, specifically used for the formation of the research methodology. Beside academic sources, also open [internet] sources such as IMO and classification societies have been used to create a better understanding of the sector, which allowed for more refined searching of useful information within the academic domain. Moreover, open sources including specific sector knowledge acting as supplementary information on topics such as regulatory frameworks and market developments have been used. The publication year of all sources used vary between 2011 and 2022.

For investigating the conceptual competitiveness of technology-based vessel dismantling, the working principles and incentives of current practices and emerging alternatives need to be made insightful. Literature research identifies that economical and financial interests have been the main incentives for the conventional vessel scrapping practices. A qualitative research on the ecological impact and social conditions of conventional practices proofs that conventional practices have a deteriorating effect on local ecology and humanitarian standards. Moreover, an analysis of the regulatory efforts for directing the vessel scrapping industry into another direction has been performed. The analysis points out that the regulatory frameworks drafted by the IMO have resulted in an unequal playing field between states that ratified or did not ratify the frameworks. Relating this to the identification of the emphasise of economical and financial importance in this industry, it can be implied that these regulations have been fuelling the gap between ecologically responsible vessel dismantling and conventional practices. This will be substantiated by means of disquisitions on the historical development and methodologies of dismantling practices, the socio-environmental impact and alternative processes.

## 2.1. Dismantling Methodologies

The literature study dedicated to scrapping methodologies and conventional processes found that historical developments of the methodologies used was related to shifts in the designated dismantling location. The geographic shifts identified could be accounted to certain drivers, from which was concluded that the ship dismantling industry is cost-based driven. This section provides a disquisition on the global market shifts and the associated processes, including the differences between these processes. These insights will form the basis for understanding the relation between conventional methodologies and the process-related factors which are important for determining the competitiveness of ecologically responsible ship dismantling processes.

### 2.1.1. History and Global Development

During the Second World War shipbreaking became a common practice in the USA, UK, and Japan due to an abundant, damaged [naval] fleet, and an increasing demand for steel. During the 1960s this practice moved to less industrialised powers such as Spain, Italy, and Turkey (“Ship Recycling - The History & Regulations”, 2019). In the early 1970s China [Taiwan] and South Korea took over the role of industry leader of ship-recycling. This was mainly cost-driven due to the difference in labour costs between South Europe and Asia. In 1986 a slight market shift to South Asia [India, Bangladesh, and Pakistan] and the Asia Pacific region [Philippines and Vietnam] was instigated by the explosion of a supposedly gas-free tanker at Kaohsiung shipbreaking berth, killing 40 workers and severely injuring 60 others (*Shipbreaking USA*, 2006).

However, China continued their scrapping activities, despite the growing competition from the South Asian countries and tightened environmental regulations. China's ship dismantling potential was emphasised by the government even further in 2013. The Chinese government introduced a promising initiative where it promoted its circular economy and low-carbon policies to enhance environmental protection and limit industrial impacts. For ship demolition the structure was based on maintaining its market through a rebating program imposed by the government, meant to incentivise shipowners for choosing a green scrapping methodology. This initiative was economically promising due to its twofold benefit for China's industry. The ship recycling industry would benefit due to an abundance of potential addressable market[1], and shipowners received an additional $200/LDT[2] if they decided to recycle their vessel at a Chinese yard (Grey, 2022). This governmental subsidy effected into a competitive price compared to Subcontinent India. However, as of 1 January 2019 China imposed a ban on the import of a large number of hazardous materials such as plastics ("China", 2019). This resulted in the ship dismantling market closing down for foreign flagged ships, and fully focusing on the inland shipping market.

The remaining non-Chinese flagged world fleet is now dependent on the very competitive Subcontinent India for vessel decommissioning. On global scale the only location capable of competing with Subcontinent India is Turkey. The presence of shipbreaking practices in Turkey is highly correlated to the local steel making industry, where ± 70% of the production capacity is EAF, and thus scrap steel dependent (N. Mikelis, 2019). Some fleet type segments, such as cruise ships, favour Turkey over Subcontinent India due to the vessels' operational area and associated demobilisation costs. Despite the fact that some dismantling companies in Turkey comply with the EU Ship Recycling Regulations, the scrapping process practised is a form of beaching named landing. Moreover, there are still concerns that the actual processes do not realise the level of compliance that is theoretically achieved ("Turkey", 2019).

### 2.1.2. Dismantling Methodologies and Processes

The development of vessel scrapping over time as described in the previous section also accompanies a development in the scrapping methodology. At first, when scrapping occurred in more developed countries after WW2, dry dock scrapping was the methodology performed. The developed countries had dry docks and experienced labour [in maritime construction] at their disposal. In the early 1970s, when the scrapping industry shifted towards Asia, quay-side floating dismantling was introduced. Currently, this is still the methodology used in China. Western countries such as the USA also performed research and pilots on this technique (Greenspan, 1984). In the case of the USA this methodology is still in practice ("Marine Recycling", n.d.).

Lastly, during the shift towards South Asia, the usage of the beaching methodology increased. Subcontinent India has an ecological advantage of a very high tide [13m] combined with a very gentle slope. Moreover, the coastal area consists of a hard rocky sea bottom (Demaria, 2010), allowing for the beaching methodology. Beaching implies a simple process and related equipment, emphasising the operational expenses within the cost composition. Since there is an abundance in cheap local labour, a very competitive sub-market is the result. The methodology of landing, as performed in Turkey, is a synthetic approach to beaching. Here, the hard rocky sea bottom is replaced by a concrete slipway ("Turkey", 2019). For all conventional methodologies the actual scrapping process is a sequential operation, visualised in figure 2.1. The process is commenced by stripping the vessel. After the preparation stage of stripping, the two-step cutting process is initiated. In the cutting process the vessel is divided into large sections at first[3], which are hauled to a secondary cutting area. In the secondary cutting area the sections are downsized to pieces appropriate for the off takers, which are steel manufacturing companies (Choi et al., 2016).

[1]Chinese and Hong Kong flagged vessels together constitute the third most populous fleet in the world

[2]LDT is Light Displacement Tonnage

[3]For beaching and landing the sections are cut from bow to stern of the vessel. For quayside scrapping this process is performed from top to bottom of the vessel

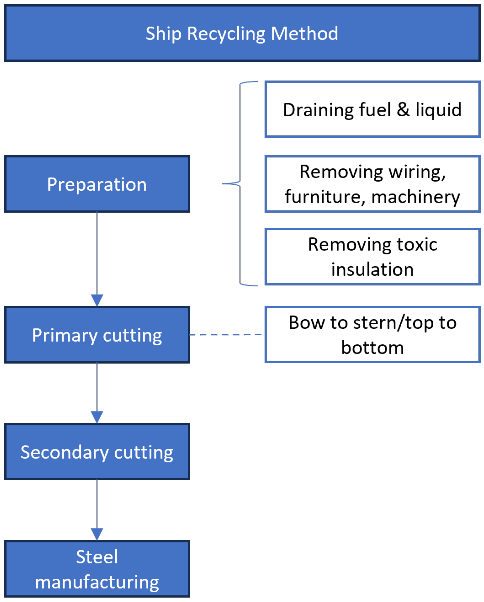



**Figure 2.1:** Conventional scrapping process

As discussed in section 2.1.1, the historical physical shifts in the vessel dismantling industry were cost-driven. However, the actual process for all methodologies remained similar as elaborated on in the previous paragraph covering the standard scrapping sequence. This implies that the cost reductions achieved are rooted in the requirements of certain methodologies. Therefore, table 2.2 provides an overview of the general methodology-related prerequisites, and capital and operational expenses.

**Table 2.2:** Scrapping methodologies & requirements

| | Requirements and conditions | Capital expenses | Operational expenses |
|---|---|---|---|
| Dry dock[4] | A dry dock and certain infrastructure is required. This infrastructure consists of cranes and a land plot. | Beside the end of life vessel acquisition cost including potential demobilisation, the dry dock scrapping approach includes dry dock lease/investment costs for construction, land plot lease/purchase, and potentially equipment purchase. | Tugs may be required for safe passage before entering the dry dock. Also, costs of energy [fuel/electricity], labour, licensing, insurance, disposal management and logistics [both for hazardous as well as outflow materials] are included |
| Quay side | A quay and certain infrastructure is required. This infrastructure consists of cranes and a land plot. | Quay lease/construction costs and capital intensive equipment required for the operation [cranes, excavators, etc.] | Costs of energy [cutting fuel/-electricity], labour [including engineering], licensing, insurance, disposal management and logistics [both for hazardous as well as outflow materials] |
| Beaching | A high tide, a gentle coastal slope, and a hard rocky sea bottom are ideal circumstances for beaching. Equipment required for the scrapping process is mostly taken from the end of life vessels [winches, cranes, etc.] | The required capital-intensive equipment is mostly extracted from the vessels [e.g. winches, cranes, etc.]. Moreover, no construction costs of land-based assets are required. | The operational expenses for beaching vary, but are extensive. Somewhere between 150-300 people are working on the vessels on a daily basis. Besides the actual labour, cutting fuel [LPG and oxygen] is required. The working conditions and rewards have low standards, resulting in comparatively low labour costs[5]. |
| Landing | A synthetic approach to beaching is landing, which is mainly used in Turkey. It is a method for beaching which can be used without the large tidal difference and rocky seabed. The vessels' aft remain afloat, whilst the bow of the ship is placed above a drainage systems. The vessel is pulled further on shore after a cut-off sections are removed, ensuring the connection to the drainage systems. | The largest capital expenses is the concrete slipway. Besides this cranes are required. All smaller equipment can be taken of the end of life vessels [e.g. winches]. | The operational expenses consist of labour, the costs of energy [cutting fuel/electricity], disposal management and logistics [both for hazardous as well as outflow materials] |

Besides the various methodology-specific costs mentioned in table 2.2, there are also costs incured by the recycling company apart from vessel purchase, which are not included in the table due to their generic nature. Examples of these costs are financing costs, insurance [related to the yard and labour force], and [import] tax and duties related to the vessel (N. Mikelis, 2019).

As can be deduced from the historical developments, the standard scrapping process as shown in figure 2.1, and the requirements and cost implications for each methodology, the trend for ship scrapping allocation has historically been cost-driven. The decision-making, from shipowners' point of view, is based minimising the cash reserves required for putting a vessel out of operation. This was enabled through the option of labour-intensive vessel scrapping, where minimal capital intensive operational requirements are needed. By choosing this option for vessel scrapping, shipowners omitted the costs of premiums arising when taking into account [ecological] regulations and developed countries labour costs. Historically, this was empowered by the geographical advantages allowing for a low technological, and thus low capital intensive, scrapping process.

Consequently, the main incentive for today's desired shift towards ecological sound scrapping practices is also expected to be economical and financial. Therefore, two elements must be elaborated further. The effect of shipowners omitting the costs associated with ecologically responsible scrapping, and the social economic result. Both including the measures devised for counteracting this decision-making.

## 2.2. Socio-Environmental Impact

From a qualitative analysis of the environmental and socio-economic impact comes forward that conventional vessel scrapping practices have a deteriorating effect on the coastal ecology of the designated locations. Moreover, literature study proofs the presence of occupational hazards resulting in injuries and work-related deaths. Also, child labour is still a proven issue in South Asia. Establishing an understanding of these issues, and the international regulatory frameworks that try to mitigate these issues, is important for demonstrating a statement on the potential need for innovation and expansion of North Western European vessel dismantling capacity. Therefore, this section provides a substantiation on the ecological and social effect of current scrapping practices, and the accessory international regulations. Also, the role of these drivers with respect to the environmentally conscience dismantling alternatives for vessel dismantling will be investigated.

### 2.2.1. Environmental Impact Studies

Several studies have been conducted on the effect of vessel scrapping on soil and sea environment in the coastal areas of different municipalities of South Asia, infamous for their extensive scrapping beaches. Studies performed on the coastal areas of Chittagong, Bangladesh indicate that the scrapping methodology as executed result in environmental atrocities, both due to the discharge of refuse materials resulting in toxic ammonia concentrations, oil spillage, and metal fragment accumulations (rust), as well as the extensive human and mechanical activity accelerating the rate and amount of shore erosion (Islam and Hossain, 1986).

Quantitative case study research has been performed on the (sub-)tidal zones of Alang, India providing insight on the high levels of Chemical Oxygen Demand [COD] and Biological Oxygen Demand [BOD]. These are measures used as indicators for water quality, which display related patterns to those in Chittagong. The discharges associated with the scrapping of vessels are pointed out as the origin of the elevated levels of COD and BOD (Demaria, 2010). Therefore, proving that the shipbreaking methodologies used in Subcontinent India substantially affect the coastal ecosystem harmfully.

[4]Sources used for the composition of table 2.2 are: ("China", 2019), ("Turkey", 2019), (Hossain, 2017), (Deshpande et al., 2013) and (Choi et al., 2016)

[5]Compared to the acquisition costs of the vessel

The Turkish vessel scrapping industry is located near Izmir, on the peninsula next to Aliağa. Besides the shipbreaking yards, the peninsula houses a large petrochemical plant. In 2000 sampling tests were conducted in the coastal area near the shipbreaking sites. From this repetitive research [4 months, spread over a year] could be concluded that in all test periods the dissolved and total levels of aluminium [Al] and iron [Fe] are above standard levels due to the existence of shipbreaking and steel industry ashore. Moreover, the levels of cadmium [Cd], nickel [Ni], and zinc [Zn] at the surface water were found to be higher than the standard levels (Neşer et al., 2008). However, since the publication of a Greenpeace report about the pollution of Aliağa associated with shipbreaking in 2002, the Government of Turkey has initiated and implemented management procedures for hazardous wastes according to Turkish law. These procedures are compliant with the Basel Convention. Therefore, the current shipbreaking practices of several yards in the area are included in the EU Whitelist. Nonetheless, in order to achieve environmentally sound management-compliance there are many gaps to close, mainly associated to the landing methodology used. Some policy recommendations for ensuring environmentally sound scrapping are made in (Neşer et al., 2008). Besides the pollution associated to specific heavy metals and substances, the emissions associated to the actual cutting process [LPG/oxygen cutting] are presumably the most pressing factor in terms of emissions. As proposed by (Deshpande et al., 2013) an average of 6.2 $kg/km \cdot mm$ LPG and 28.5 $kg/km \cdot mm$ oxygen is required for cutting in the primary and secondary cutting phase of conventional vessel dismantling. As shown in table 2.2, LPG/oxygen cutting is used both in South Asia as well as in Turkey for primary and secondary cutting.

Besides studies containing a more generic environmental impact analysis on the presence of shipbreaking in the area, root cause analysis for the presence of hazardous metals such as mercury have also been performed on Gadani, Pakistan. It has been determined that the Gadani shipbreaking area is contaminated with mercury, linked to the dismantling methodology of beaching. Moreover, concerns arise that measures performed on the beaches do not quantitatively reflect the amount of mercury that has been released at the shipbreaking areas. The reason proposed for this is the hazardous metals being washed out into the marine system with the tide (Kakar et al., 2021). This assumption aligns with the more general impact studies with a focus on the entire coastal are, and not only the beach, and is therefor deemed plausible.

Research performed on the environmental and ecological impact of coastal areas housing ship dismantling in South Asia have the unambiguous conclusion that beaching as a ship dismantling method is not environmentally responsible. The main cause identified is the minimal procedures and enforcement of proper waste management, both in terms of air pollution, landfill, and spillage into the sea. However, the recyclability of the maritime industry in general has potential due to its volume. Therefore, vessel recycling is justified from an environmental point of view, but the prevention of these consequences of conventional scrapping are deemed of importance for technology-based dismantling concepts.

### 2.2.2. Regulations and Hazardous Waste Management

It can be argued that end of life ship scrapping contributes to sustainable development and represents an environmentally friendly method for the disposal of ships. For the recycling or reusing, thus useful end of life economical contribution, of ship-grade steel[6], machinery and auxiliaries, and even interior (e.g. galley equipment) an integrated system is required. Through this boundary condition, ship-recycling facilities in general are an environmental friendly way of the disposal of decommissioned ships (N. Mikelis, 2006). However, ships compose not only of various recyclable or reusable materials, but also of many hazardous and toxic materials such as asbestos, PCBs, and Ozone Depleting substances (Yan et al., 2018). For European States and Member States of the Organisation for Economic Co-operation and Development (OECD) such substances are subject to monitoring (i.e. IHM), and their disposal is regulated strictly due to the 1989 Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal. There are three possible methods for the disposal of hazardous materials, analysed for and included in the Hong Kong Convention ("Recycling of ships", 2009):

[6]Ship-grade steel is used in offshore and marine engineering. Ship-grade steel has higher strength than regular construction steel to minimise structure weight, without losing strength and stiffness of the structure. Common grades include A, B, D, E, AH32/36/40, DH32/36/40, EH32/36/40, etc., ranging for different strengths.

1. *Decontamination prior to export* - Shipowners organise the removal of hazardous materials [onboard and contained in the ship's structure] before scrapping. After inspection and proper waste management the ship would not fall under the Basel Convention during scrapping.
2. *Environmental sound on-site management* - During [early stage] scrapping hazardous materials are safely removed and disposed. This option requires narrow monitoring and inspection [IHM compared to reality].
3. *Dumping of hazardous materials* - During scrapping no attention is paid to disposal of hazardous materials allowing them to be freely released into the environment.

Options 1 and 2 imply high costs associated with the strict monitoring and disposal, and/or required expertise and technology for the removal of the hazardous materials, which will directly increase the scrapping costs of ships. South Asia has used the third option ever since the shipbreaking industry started flourishing in this region (Srinivasa Reddy et al., 2003).

Moreover, through the ratification of the Basel Convention by committing states to control the movement of end of life vessels, a multitude of competitiveness problems arise. The required communication between the importing and exporting State is very time consuming, but it does not influence the quality of the shipbreaking practices - at best the transparency of the industry. Moreover, the operating managers of the vessel will most likely have no direct relation to exporting State [i.e. the Flag State]. Most importantly, a number of developing countries do not acknowledge the Basel Convention, resulting in a even more cumbersome communication process [i.e. the importing state does not have to comply with the Basel Convention] (N. Mikelis, 2019). Also, the implementation of such conventions require local enforcement of committing states. This also creates an uneven playing field, because developing countries lack the required resources for adequate monitoring, implying that money should be allocated for training activities before proper enforcement ("Enforcement", 2011). From these competitiveness problems can be concluded that a non-uniform ratification of policy creates a more uneven playing field. As a result from this, the ship-recycling industry can rely on developing countries for the disposal of decommissioned ships to omit the financial burden of complying with rules for end of life ships established in the 1989 Basel Convention (Chang et al., 2010).

### 2.2.3. Socio-Economic Impact Studies

There is a vast difference between Western and South Asian labour costs and job-related rights. This includes correct training for personnel, adequate emergency services and enforcing authorities for ensuring fair labour conditions. A study performed in 2014, in collaboration with the Gujarat Maritime Board (GMB), on the effect of the implementation of training for ship-recycling workers in Alang, India showed a decrease in fatalities[7] (Hiremath et al., 2014). However, ship-recycling is globally still considered one of the most dangerous industries (Mishra, 2018). Subsequently, health issues and occupational safety issues emerge during the scrapping of vessels - resulting in casualties especially in South Asia (Bangladesh, India and Pakistan) ("The Human Costs", 2019).

Attention from the world community with regards to pollutants and occupational safety & health issues during vessel scrapping has increased throughout the International Maritime Organisation (IMO), the International Labour Organisation (ILO), and the European Union (EU) ("Recycling of ships", 2009; *Guidelines for Safe and Environmentally Sound Ship Recycling*, 2012; *Regulation on ship recycling and amending Regulation (EC)*, 2013). The Hong Kong Convention includes, among others, a clause aiming to ensure that ships do not pose any unnecessary threats to human health and safety at the end of their operational life time. The European Ship Recycling Regulations also enhances the protection of environment and human safety during scrapping, focused on Europe. However, in South Asia incidents still happen on a regular basis. Commonly occurring accidents often find their origin in fire and explosions, falls from heights, the truancy of occupational training (e.g. working with blow torches), not wearing protective equipment (e.g. helmets), working in confined spaces, and working with hazardous materials (Chang et al., 2010, *Safety and Health in Shipbreaking: Guidelines for Asian Countries and Turkey*, 2004).

[7] 2.0 fatalities per 1000 workers in 1995-2005, compared to 0.13 fatalities per 1000 workers in 2003-2011 [as per official GMB records]

Besides occupational hazards and safety shortcomings, there is also the presence of child labour. Especially during the night the percentage of labour force under the legal minimum working age is high, as the outcome of the investigation of (Chowdhury, 2020) concluded. In comparison with years before a downward trend was visible in the percentile of child labour. However, during the day an average of 8% and during the night an average of 20% of the working force is under the legal working age for hazardous work, as proposed by local regulation. Therefore, the percentage of child labour averages out at 13%.

## 2.3. Alternative Dismantling Processes

Currently, there are many initiatives emerging on global scale claiming to have an environmentally sound solution for the dismantling and recycling of end of life vessels. However, non of these concepts are operational on a commercial scale. At present *Elegant Exit Company* and *Leviathan GmbH* seem to be the front runners. *Elegant Exit Company* for the acquisition of the vessel *Wan Hai 165* ("Wan Hai 165: From Approval to Action – EEC and ASRY's Ship Recycling in Motion", 2023), and *Leviathan GmbH* for reaching an agreement on yard usage in Stralsund, Germany ("Leviathan Plans Sustainable Ship Recycling Facility In Germany", 2023). The essence of all concepts emerging is switching from a labour intensive dismantling process towards a more technologically enhanced process, allowing for a higher offset volume. This implies a shift in the business model. Where the industry was cost-driven pushed towards developing countries with cheaper labour, as explained in section 2.1.2, environmentally sound dismantling concepts focus on a business model where throughput is key and the initial investment costs are leading. The implications in terms of the distribution of expenses switches from OPEX intensive to CAPEX intensive. This is visualised in a simplified matter in figure 2.2.

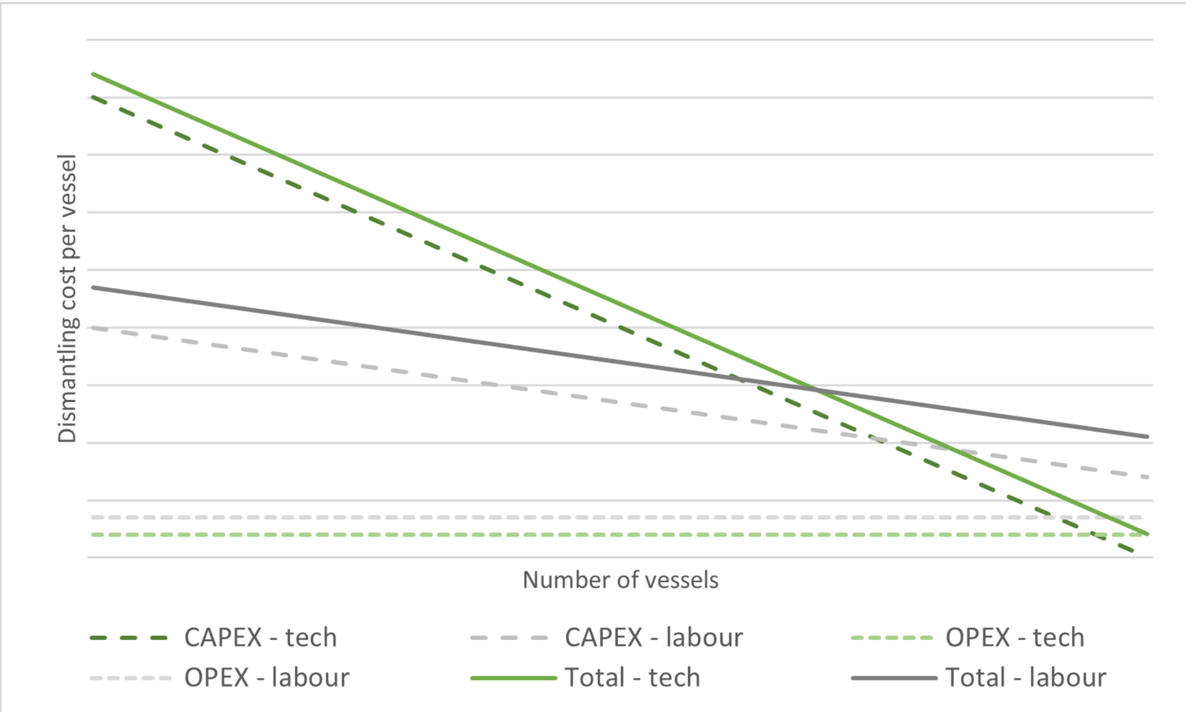



**Figure 2.2:** Simplified expenses of dismantling operations

An initial judgement on the level of sustainability with regards to ship recycling practices can be made based on the work of (Sant' Ana et al., 2023). Here, a measurement model is proposed which makes use of an exploratory factor analysis (EFA), with the objective to reduce the quantity of sustainable variables to the most relevant ones in terms of interdependence with a certain practice. The factor loadings between the variables and practices represent the relation between the two, derived through the EFA method [figure 2.3]. The identification of variables for sustainable practices within the ship recycling supply chain are ensured through face validity. The research found that the identified factors related to managerial and social practices are of particular importance in relation to the measuring and comparing of the level of environmentally soundness of the different emerging dismantling concepts. Such factors include adequate training for employees and employee health, awareness of hazardous materials, and the monitoring of environmental conditions of recycling facilities. Many of the social and environmental issues identified by the best practices of (Sant' Ana et al., 2023) and analysis presented in section 2.2, are coped with by means of a technological solution. Through this, the emerging initiatives attempt to minimise errors and maximise sustainable practices, while offering a commercially viable solution.

When looking at the outcome of the ship recycling measurement model, visible in figure 2.3, one can identify several streams within the dismantling value chain where the green alternatives are offering potential solutions to. The process related phases are the cutting of the vessels, and cleaning the outflow materials to the demanded standard. Besides the direct process related phases, the transportation [which is twofold; both demobilisation as well as the transportation to the offtake parties] is also important for the overall ecological impact of the outflow products. Moreover, the social implications of conventional ship dismantling are mitigated towards technological solutions, minimising manual labour and danger. These aspects are also heavily emphasised by (Sant' Ana et al., 2023). Therefore, it can be concluded from the relation between emphasising technology in the process decisions, and the sustainability measurement model proposed by (Sant' Ana et al., 2023) that technology-based vessel dismantling offers a more sustainable option than the processes executed at conventional methodologies.

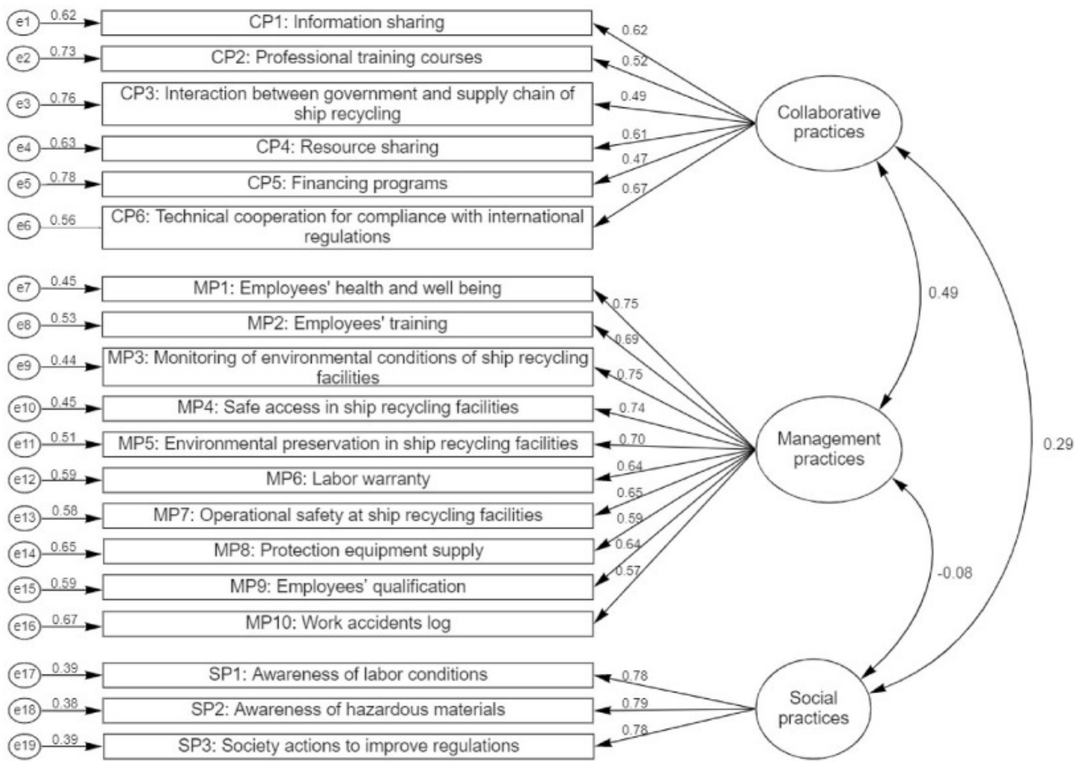



**Figure 2.3:** Measurement model of sustainable ship dismantling practices (Sant' Ana et al., 2023)

Research related to the process analysis of technology-based vessel dismantling is currently non-existent. Also, research on the potential economical performance of technology-based vessel dismantling compared to conventional scrapping has not been found. The only work dedicated to sustainable ship dismantling practices by means of presenting a conceptual framework and modelling of factors influencing the sustainability measurement is published by (Sant' Ana et al., 2023).

## 2.4. Conclusion

The purpose of the problem analysis was to investigate the need for an economically feasible, sustainable ship dismantling concept. Through an historical analysis an understanding of the drivers and workings has been created. Substantiations have been provided for the centralised role of economic and financial incentives within this industry. Also, the implied emphasis of these themes in the context of more sustainable, technology-based dismantling concepts have been discussed. Furthermore, the scope of adverse consequences of current practices have been discussed, including the environmental effect and socio-economic conditions associated with current practices. The qualitative research on the relation between commonly used dismantling methodologies and coastal deterioration and pollution provided a causality. Moreover, the difference in labour standards between the developed and developing countries has been scrutinised. The difference manifests itself in occupational hazards in the dismantling industry, and even proof of illegalities such as child labour have been found. The analysis dedicated to the regulatory frameworks drawn up to mitigate these environmental and social adverse impacts concluded that without a uniform global ratification of the legislation, a more unequal playing field results.

The international concerns regarding the impacts of conventional vessel dismantling resulted in the emergence of green, alternative dismantling concepts. Examples of these concepts are *Elegant Exit Company*, *Leviathan GmbH*, *Atlas Decommissioning*, and *Circular Maritime Technology*, which are established in developed countries. Overlap in these concepts is shifting away from labour intensive processes, and focusing on technology to cope with the adverse impacts of the conventional process. This implies a transition from an OPEX intensive process to a CAPEX intensive process. Academic research used to substantiate the complications arising from current practices are mostly focused on the ecological impact of the coastal areas, and the socioeconomic environment of shipbreaking and its deficits at the presently used geographic locations. Research on sustainable dismantling concepts only exist in terms of a qualitative framework model for the relevant parameters enabling sustainable dismantling (Sant' Ana et al., 2023). Also, research has been found dedicated to the vessels' potential and role in sustainable dismantling (Jain, 2017). However, no research is concentrated on the process of environmentally sound, technology-based dismantling, or the dismantling potential of developed regions such as North West Europe. Research dedicated to the individual added value components of such concepts, intended as mitigating measures for the described adverse impacts, is currently non-existent. Furthermore, an approach for monetising these process adjustments into the business model, allowing for a single unit comparison of the technology-based concepts to conventional dismantling methods is missing in academic work.

CAPEX intensive dismantling would require a large throughput to be competitive with conventional alternatives, argued from an economic point of view. The framework for emission reporting on all company activities create an economic drive for steel manufacturing companies to administer less environmentally pressing operating methods. One of the most promising methods is EAF, where feedstock procurement in the form of high quality scrap steel is a concern for meeting production demand. This expected increment in demand and large required throughput volumes of technology-based dismantling could form a complimentary industry. Through creating an understanding of the level of competitiveness of dismantling concepts with a technology centred process, potential required governmental or industry subsidies and incentives can be made tangible, that would allow for an equal level playing field with current practices. The findings stated in this chapter form the basis for establishing a scope that allows for such comparisons and insights.

# 3
# Research Methodology

Current research on the vessel dismantling industry focuses on the adverse consequences of the methodologies used, as elaborated on in chapter 2. No academic work is dedicated to the process of environmentally sound, technology-based dismantling, or the dismantling potential of developed regions such as North West Europe. Moreover, no research is performed on the economic result derived from such operations, that would potentially provide a justification for the required investments of technology centred dismantling. Summarised, there is a lack of investigation on technology-based process analysis, process phases individual added value, monetising the ecological and social unburdening of technology-based dismantling, and developed countries as a geographic setting. This section will provide substantiation for which research and modelling methodologies have the most fitting purpose for covering the described knowledge gap. The findings per scope element will be presented and individually justified by means of literature research. First, the research structure and scope will be identified and elaborated on.

## 3.1. Structure and Scope

The aim of this thesis is to provide an understanding on the process of technology-based vessel dismantling, and how such concepts perform economically compared to conventional scrapping processes. As proven in section 2.1.1, shipowners are historically incentivised by economic and financial factors for end of life vessel management. As provided in section 2.2.2, the regulatory frameworks aiming to improve the conditions and effects of vessel dismantling have created an unequal level playing field between member states that ratified the rules, and non-member states. Especially with respect to adequate waste management this poses significant economic consequences. This implies that investigating the economic effect of transitioning from labour-based OPEX intensive dismantling towards technology-based CAPEX intensive dismantling must take into account the monetising of ecological and social unburdening effect of technology-based vessel dismantling. For this a clear scope and approach must be defined first.

The first step is to establish the extent of the process deemed important for the purpose of this research. Several factors have been considered while determining the scope: the inclusion of the ecological effect of the process, the operational requirements of a large throughput volume, and the presence of the shipping industry in North West Europe. This resulted in setting the demobilisation of the asset to be dismantled as boundary one. Secondly, there is a vast difference between the environmental effect of different steel manufacturing methods, as explained in chapter 1. Moreover, the emission chain reporting applicable in the EU provides an incentive for EU-located steel manufacturers to investigate emission lowering production methods. This does not apply to steel manufacturers located in the conventional scrapping locations: South Asia and Turkey. Therefore, the other boundary of the scope is set at the steel manufacturing.

In between the two boundaries, there are some process-related key insights to be gained to provide a comprehension of the level of competitiveness between technology-based and conventional dismantling. The first step is to determine the feedstock for the dismantling process. Since there is a large local presence of shipping and the effect of the demobilisation is included in the scope, a market dynamics research must be performed to provide insight on the naturally berthing commercial segment and size. Secondly, a material quantification of the selected fleet of interest must be performed to determine the amount of materials which can be expected, forming the base line for the revenue stream. It has been decided that the main focus is on steel. This results from the regulatory incentives for operational adjustments in steel manufacturing implying different feedstock, and the composition of ships equalling 72-85% of recyclable steel (Choi et al., 2016), depending on the vessel type and size. Thirdly, a process analysis on the annual throughput capabilities and requirements of technology-based dismantling must be determined. From the process analysis initial insight can be established for the economic streams associated with technology-based dismantling. For an adequate comparison to conventional practices, methodologies must be selected for the inclusion of the monetised environmental and social unburdening effect. Lastly, the process and all required phases must be mapped to determine the added value of individual phases. After the threshold for technology-based dismantling is established, the scenarios for comparison can be determined. Also, relevant sensitivity studies related to the process and market dynamics can be identified. This approach and structure for the scope is be visualised in figure 3.1, where the interdependence of the elements are emphasised by the black arrows including denotations.

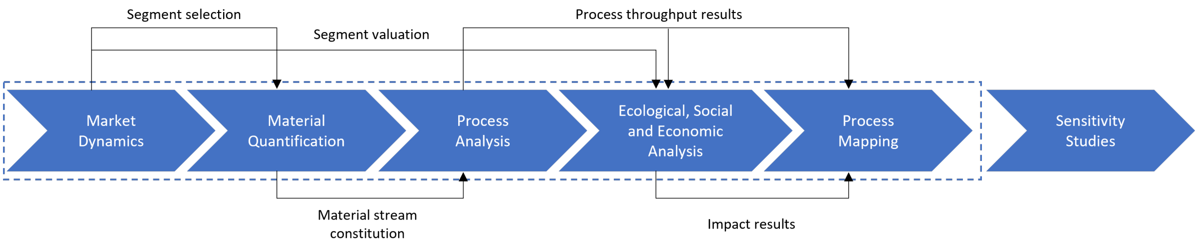



**Figure 3.1:** Scope

The literature used for defining this research structure is based on current research deficits, as described in the conclusion of the problem analysis and the introduction of this chapter. Besides the keywords that were already mentioned in chapter 2 several key words are added corresponding to the research deficits. These keywords are: *feasibility study*, *Value Stream Map*, *LCA Comparison*, *Lean*, *Eco-efficiency*, *Life cycle sustainability assessment*, *eco-costs*, and *ecological allocation*. To determine the relevancy of papers the a decision-making structure was followed consisting of:

1. The title of the papers in relation to the problem analysis
2. The abstract and conclusion of the papers in relation to the problem analysis

This resulted in an additional 10 papers. Moreover, open sources including specific sector knowledge acting as supplementary information on topics such as market dynamics have been used. Examples of these open sources are *Clarksons*, *Roben des Bois*, and *Marine Traffic*. Also, reports published by sectorial experts and institutions such as (N. Mikelis, 2006), (N. Mikelis, 2019), (N. E. Mikelis, 2008) will be used for ensuring a market understanding with respect to past and current practices.

## 3.2. Market Dynamics

In order to determine the appropriate feedstock for technology-based dismantling in the designated region, a market dynamics analysis must be performed. Through this market analysis the world fleet will be scaled down to a segment offering a reliable input. From this process, the material quantification method can be shaped according to the fleet segment of interest. Moreover, the pricing strategy allowing for cost allocation of the vessel acquisition in the economic model can be determined through this.

Potent feedstock is essential for operational and economic success of technology-based dismantling, as stated in section 2.3. The market dynamics analysis will be structured by means of a top-down feasibility study, argued from the commodity supply chain transported by vessels. This is an adaptive interpretation of the first of Porter's Five Forces, where the potential feasible commercial segments are viewed upon as competition. The theory describes for competition in the industry that the larger the number of competitors, along with the number of equivalent products and services they offer, the lesser the power of a company ("Porter's 5 Forces Explained and How to Use the Model", 2023). This is circumscribed to the larger the number of vessels within a commercial segment, the larger their power in the applicability as feedstock option.

The top-down feasibility structure comprises of analysing the commercial fleet in North West Europe by means of used trade routes, ending at certain ports. After identifying the largest ports in terms of port calls and transshipment volume, the naturally berthing fleet segment can be obtained. It is argued that the local presence of feedstock provides advantages with respect to the acquisition price and demobilisation footprint. Since no demobilisation to the demolition yard is required, no cash reserves for demobilisation have to be taken into account by the shipowner. The required data can be obtained via *Clarksons* and *Marine Traffic*. After identifying the commercially present segments strongly present in North West Europe, the feasibility for dismantling this segment can be investigated. For this a statistical test on the average fleet age and dismantling age will be performed. If the commercial classes are too newly build, the commercial class does not provide an adequate feedstock. In the case that the average fleet age of a commercial class does not approach dismantling age, the decision can be made to find an alternative commercial class, or eliminate the specific class. The essential high throughput for technology-based dismantling is expressed in LDT. This implies a significant amount of smaller vessels, or enough larger vessels to achieve this need. After the local analysis in terms of feedstock applicability is performed and tested, the obtained segment of interest is framed in an international picture. This allows for a dismantling potential test on global scale, audited on historical data. Furthermore, it is of importance to investigate potential deviations in the relation between dismantling age and the size class of interest. For this check historical trends can be used.

For inclusion in the economic model, the end of life vessel valuation per region must be determined. For this data from *Clarksons* and *Robin des Bois* will be used. Here, the most crucial element is the availability of data. Since the shipping industry, and the dismantling industry specifically, is known to be opaque this could pose a challenge. Also, the decision-making on what elements to include in the valuation is important. To align with the scope, the demobilisation costs must be determined. For this a fictive journey to a demobilisation location will be calculated. The fleet segment of interest as determined by the methodology described above will be uphold. Case studies will be obtained including drive configuration data for these calculations. The sailing speed used will be the design speed derived from (Papanikolaou, 2014). The calculation for the required amount of bunker fuel will be performed following the propulsion train as proposed in (Woud and Stapersma, 2016). With a location dependent bunker price selection the monetary implications of the demobilisation expressed as $/LDT can be obtained. Understanding the relation between design parameters of vessels, and using this interconnectivity, is a common approach in ship design (Papanikolaou, 2014). Therefore, it is decided to make use of a holistic approach in the case that data enlargement is required for a reliable valuation of the segment.

## 3.3. Material Quantification

The material quantification is a principle aspect of the research as it comprises the theoretical output of the process, and the output determines the economic result of the process. Therefore, it is important to make a consideration on the possible procedures for quantifying the outflow materials. The preferred option for information gathering is through construction documentation of vessels. Besides information from shipbuilding companies, there are various applicable models for material quantification. Since the level of accuracy is key, it is important to investigate how each method copes with deviations in the construction of vessels, as well as non-transparency with respect to dangerous materials. Usage can be made of comparable industries to derive possible models. After identifying the possible options, it must be decided which information and model is deemed the best fit to act as input for the process analysis.

As proposed in (Jain, 2017), there is an overlap in the approach and workings of recycling in the aviation industry as well as in the automobile industry. For the aviation industry the resemblance can be found in the recycling approach [economically valuable components are disassembled], while the earning model of ship recycling finds similitude with the automobile industry [EoL value is based on weight of materials with intrinsic market value]. It is argued that the difference originates from the non-existing market for reusable components of automobiles, and the high-frequency of relatively small components present in automobiles (Sakai et al., 2014). Ships on the other hand have, similar to aircrafts, relatively large components, with a much more intermittent and densely integrated frequency.

Despite the certain level of scepticism in the maritime recycling industry towards sharing data and information, some studies have been performed on the material quantification of EoL vessels. Through the findings of the literature study performed by (Jain, 2017), it was deduced that four methods have been used in research for quantifying material streams. This includes sampling of ships (Andersen et al., 1999), sampling on the beaches of yards (Srinivasa Reddy et al., 2003), interviews of ship recycling parties (M., 2010), and an input-output model based on approximate historical data (Hiremath et al., 2015). All studies are focused on the environmental and ecological influence of ship breaking through their waste streams. Also, a study has been performed in collaboration with *Det Norske Veritas* that focuses on the weight distribution and material quantification per model instead of per yard, in comparison to the other studies (Andersen et al., 2001). It is substantiated by both (Andersen et al., 2001) and (Jain, 2017) that the material composition determined per fleet type using an empirical estimations deduced from ship design literature is most accurate in dealing with the uncertainties.

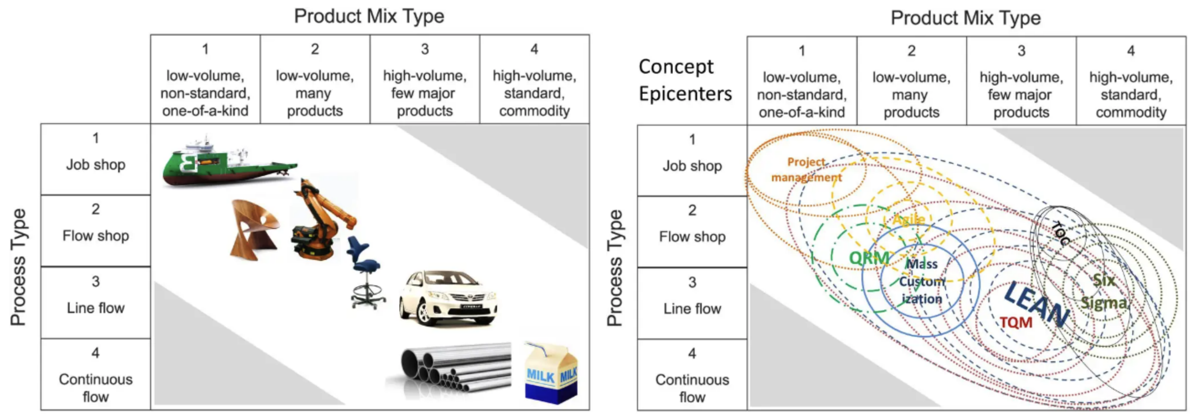
However, it is acknowledged that inaccuracies in the weight distribution estimation, divided into weight associated with machinery, outfitting, and steel, arise due to operational alternations to the vessels, resulting in quantification uncertainties. Considering the amount of literature reflection on existing research regarding material quantification, the methodology for lightweight distribution elements to material streams as proposed by (Jain, 2017) is deemed as sufficient for bridging the material assessment to the operational and earning model. This method is deduced from (Andersen et al., 1999) and (Andersen et al., 2001), where the sampling of ships on was the approach for material quantification. This approach could provide challenges in obtaining information form shipbuilding companies. As has been substantiated in section 3.2, the vessel types comprising the scope of this research will result from a market dynamics research focused on North West Europe.

The material quantification as proposed by (Jain, 2017) only includes a 2006 built Handymax bulk carrier. The format providing the relation between weight list items and material elements is considered as clear, and relatable to monetary streams. However, in the case that the documentation of not enough sample ships can be obtained, weight reallocation methods must be investigated. The reallocation of commercial class specific weight classes is deemed achievable [e.g. piping, tanks, and cargo-related machinery of a tanker]. However, this does decrease the reliability of the material quantification. If no shipbuilder weight lists can be obtained to establish material quantification, weight element and waste reallocation of a known weight list will be performed by means of the work presented in the overviews of (Rahman and Kim, 2020), (Jain, 2017), and (Martin et al., 2016). By means of this approach an accurate bridge can be established between the operational input and economic result.

## 3.4. Process Analysis

The approach for analysing the operability of technology-based dismantling is crucial for comprehending the translation of the input for the process as obtained through the approach described in section 3.3, to the economic result of technology-based dismantling. To perform a process analysis, and make the outcome comparable with conventional scrapping processes, an operational demarcation needs to be established. The reason for this is to be able to have comparable grounds for the labour-based and technology-based dismantling. Therefore, it was decided that a one-year simulation of both operations will be established. For the simulation of the technology-based dismantling process a case study need to be decided on to act as a red line for the modelling. The decision-making for the case study will be explained in chapter 4. The comparison scenarios for conventional dismantling processes will be elaborated on in section 3.7.

First it is relevant to identify which Key Performance Indicators [KPIs] are deemed crucial for technology-based dismantling. Direct identification of these KPIs is challenging due to the limited research that has been performed on this subject for the ship dismantling industry. However, one can look at comparable industries, or draw the parallel between the dismantling process and the construction process. The characterisation of a technology-based dismantling process can be used to narrow down the options for process identification methods from lean optimisation through Hayes and Wheelwright's product-process matrix, which also points out possible relatable industries. The framework for narrowing down the appropriate techniques is as proposed in (Hayes and Wheelwright, 1984), and visible in figure 3.2. From the process description provided in section 2.3 and figures 3.2 can be concluded that the concept epicentre is a flow shop with a high volume and few major products.




**(a)** Product-process matrix

**(b)** Lean Concept Epicentres

**Figure 3.2:** Hayes and Wheelwright's process-product matrix Netland, 2020

For the establishment of an adequate methodology for analysing environmentally sound dismantling processes an introduction to the process key elements is provided in section 2.3. Most of the process steps are sequential with parallel supporting facilities. Here, labour intensive work is replaced by machinery, where the turnaround time for every phase step is dominant for operational success. Therefore, it is of importance for identifying the operational congestion points. Through identifying the location and number of congestion points, a mathematical equation for the throughput time per commercial segment can be formulated. After identifying the steps proposing as bottlenecks, the next item of interest is the utility usage of the conceptual facility. This is important for the economical and ecological impact of the process phase, and the entire operation. The annual throughput and utility usage will allow for approximating the operational expenses and gains per commercial segment.

Subsequently, the findings of this analysis, per process phase, and the economic implications must be mapped accordingly. More detail on the mapping method decision-making is proposed in section 3.6. For identifying the accessory added value or costs of a certain phase, adequate process KPIs for substantiation must be identified. As mentioned in section 2.3 and 3.2, it is expected that the main economical added value comes forth from the process volume. Within the process this translates itself to process phase speed. Furthermore, the KPIs must take into account the relevant parameters for including the ecological and social unburdening effect of technology-based dismantling. The measurements for sustainable ship recycling practices as covered in section 2.3, and proposed by (Sant' Ana et al., 2023), are mostly related to supporting facilities required for ship dismantling. Therefore, these will be included indirectly in the considered KPIs, listed in table 3.1.

**Table 3.1:** Key Performance Indicators

| KPI | Unit | KPI | Unit |
|---|---|---|---|
| Total lead time | hours | Process water added step "X" | $m^3$ |
| Total value added time | hours | Material usage [cutting loss] step "X" | t |
| Lead time phase "X" | hours | Total energy consumption | kWh |
| Value added time phase "X" | hours | Total added energy | kWh |
| Process water required | $m^3$ | Investment Requirement phase "X" | €/$ |
| Operational Expenses phase "X" | €/$ | Hazardous material generation phase "X" | t |

## 3.5. Ecological, Social, and Economic Impact Analysis

Quantifying the ecological, social and economical impact of replacing labour intensive work with technology centred work is principle for technology-based vessel dismantling concepts. By monetising the unburdening effect and showing the true price difference in dismantling methods, the differences between economic results of technology-based and conventional dismantling can be made tangible. Research on quantifying the ecological and social impact of processes showed a multitude of modelling opportunities. This section will provide substantiation on why the most applicable and comprehensive value index method is the eco-costs approach. The eco-costs approach can be implemented directly into the process value of a company by means of the sustainable net present value. For micro-economic scale this economic model is referred to as the sustainability profit. The decision-making process on the suitability of the sustainability profit will be elaborated in the last sub-section.

### 3.5.1. Ecological and Social Impact Analysis

Quantifying the ecological and social unburdening influence of individual phases and technologies is crucial for understanding the effect on the overall process. Due to anticipated data uncertainties, parallels to relatable industries must be made. One of the most emphasised aspect of the business model of technology-based vessel dismantling is commercial viability with a minimised ecological footprint. The considerations for selecting the best fitting methodologies for this thesis purpose are the following. First, the different frameworks and methodologies for accounting ecological and social impact of processes need to be considered. Furthermore, it is relevant what parameters the methodologies include in the expression of this impact. Besides evaluating the options and justifying the decision-making, data accessibility must be taken into account. Also, the goal of a single unit comparison between conventional and technology-based dismantling must be taken into account whilst considering possibly suitable accounting methods.

For assessing the ecological impact of a process, parallels can be drawn to different industries. Multiple assessments on the key factors/indicators affecting green ship recycling have been performed. As mentioned in section 2.3, the best practices for green recycling have been investigated by (Sant' Ana et al., 2023). Moreover, specifically for Chinese yards (Zhou et al., 2021) provide a literature study and interviews with scholars of the China National Shiprecycling Association, managers, and workers in ship recycling yards [survey] in order to verify the findings. However, the research aims for providing insight in the interrelationships among the factors influencing the green shipping recycling [i.e. on an aggregated level], whilst this research is more focused on the operational workings of technology-based dismantling and the resulting level of competitiveness of such concepts. Possible frameworks for evaluating ecological impact are the associated matrix method, the index value approach, computer program models, and the descriptive resource analysis model (Lapping, 1975).

Firstly, for the associated matrix model a cause-and-effect matrix system is utilised in order to describe the potential impacts of a project or process[step] through a comparative approach. Through an axial system representing various development alternatives, and environmental impact, a significance rating is provided assigned to all options. Beside the fact that the method is only as comprehensive as the value judgement of its creator, it also only provides qualitative insight in cause-and-effect relationships (Leopold et al., 1971). Therefore, this method may be used for understanding the relationships between certain process steps of technology-based vessel dismantling and the [overall] environmental impact, but it is not a suitable method for quantifying the impact.

Secondly, the index value method is designed to compare the consequences of several different action paths within a system or process. The model is formed by a set of quantified quality indicators, which are applied to a set of development alternatives. The different impacts of the various development alternatives are represented by the assignment of several weight factors to each individual environmental characteristic. Similarly to the associated matrix model a cause-and-effect methodology is followed. However, the difference is that the index value method is not one-dimensional, but it can demonstrate linkages and feedback on several levels within the entire system. This suggests that the index model can show interactions of the different impacts.

Thirdly, the computer program models. This method for modelling the environmental and ecological impact for technology-based vessel dismantling would require an enormous amount of data to achieve the level of accuracy required. The distinction between the method and the means lies within the definition of the computer program model. Computer-based methods are designed to take the consequences of one particular action all the way through to their conclusion, instead of being comparative. The analysis must then be rerun for each alternative action, as a separate iteration (Lapping, 1975). However, one can argue that modelling a methodology with a set of standardised indicators providing a quantification of the ecological impact is a computer program modelled version of the value index methodology. Moreover, creating a dedicated computer programme specifically for technology-based vessel dismantling concepts would exceed the requirements for reaching the goal, which is gaining insight in the competitiveness of the concept, among others through its environmental impact.

Lastly, the descriptive methods for environmental impact assessment are more inventorying focused and therefore, similar to the associated matrix method, more relevant for qualitative and descriptive research, rather than having quantifying needs.

**Table 3.2:** Environmental impact calculation methods, (Ettema, 2021)

| Method | Multi-to-single | Damage-oriented | Problem-oriented | Remarks |
|---|---|---|---|---|
| CML2001 | X | | X | Focus on chemical risks. Not comparable |
| Eco-indicator 99 | X | X | | Allows for comparison of processes/impacts |
| Eco-costs | X | X | | Comparison on cost origin possible, social effects included too |
| EDIP97 | X | | X | Material properties focused |
| Impact2002+ | X | X | | Based on Eco-indicator 99 |

Considering the purpose of providing insight in the ecological and social influence on process phases, modelling the index value method is the most suitable technique. There are different methods following the index value framework for providing concrete indicators. Some of the methodologies that have been investigated are displayed in table 3.2. The goal of quantifying the ecological and social impact must be scoped to determine the most suitable method. The objective is to express the ecological impact in a monetary sense, to provide a single unit comparison between technology-based vessel dismantling and conventional practices. Moreover, it would be favourable to be able to provide an understanding of the underlying structure of this monetary expression. Insight in the main focus group of emissions, green house gasses [or GHG-equivalents], is also deemed important. For this the single use system of carbon footprint will be used. Here, the direct relation to a certain combustion process as a result of for example transport is evident. Therefore, an expression for the amount of $CO_2$ emissions for a certain process step is deemed achievable by means of creating an understanding of the underlying process [i.e. for example determining the aggregated bunker quantity required for a certain logistics, and identifying the appropriate emission equivalent]. Furthermore, it is argued that a damage-oriented method is more suitable than a problem-oriented structure, because to a certain level the technology-based dismantling will also generate an ecological impact, and the area of interest is the difference between this impact and its alternatives. After extensive research on different methodologies and their advantages and disadvantages, the eco-costs approach is declared the most suitable quantification method. Figure 3.3 provides an overview of the general framework and workings of the eco-costs theory.

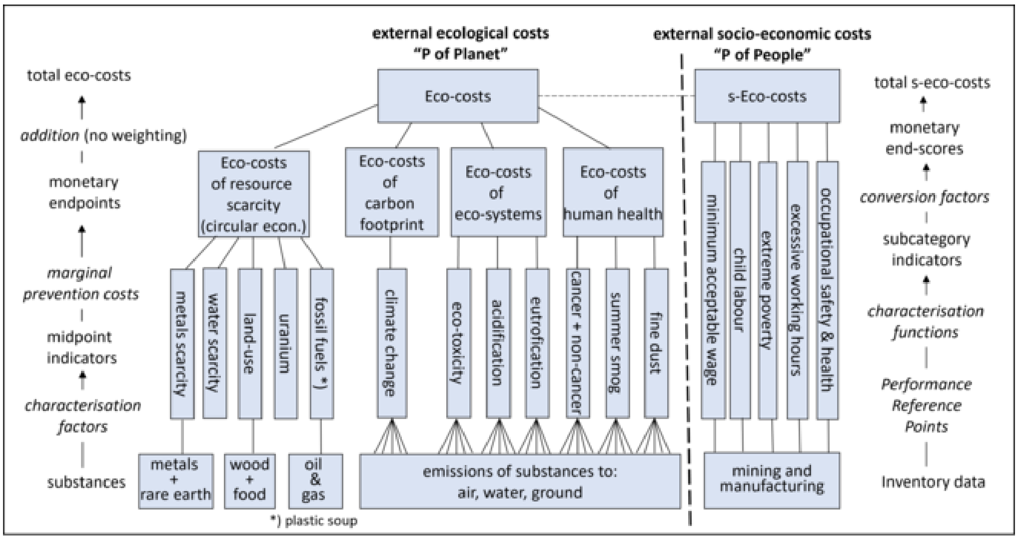



**Figure 3.3:** Ecological and social eco-costs structure

Reasons for choosing the eco-costs method besides that it is suitable considering the goal of expressing the ecological impact in a monetary format, is the availability of data ("Eco Costs Value", 2023) and the structure and items included in the cost establishment as shown in figure 3.3. These themes align perfectly with the roots of the global criticism on the current practices within vessel dismantling. Furthermore, the method also provides indicators in the social category, again with themes aligning with the global criticism such as child labour and occupational health and safety.

### 3.5.2. Economic Analysis

To determine the economic level of competitiveness in comparison to conventional practices, the investment requirements for the needed equipment must be approximated through literature. Through this approximation and a financing scheme, the annual CAPEX costs for the equipment can be defined. Moreover, through establishing a price per phase related assets, the added value compared to the CAPEX influence can be assessed. The origin of the added value can be found through monetising the economic, ecological and social added value originating from phase "X"[1], and relate this to the overall process. The intrinsic added value of the process will eventually be determined by the product offtakers through their interpretation of the value [supply and demand of free market economy]. The expected added value from process-related decisions resulting in a higher quality product, through a circular process, imply monetising the non-economic value of the process. As stated in section 3.5.1 the eco-costs approach is suitable for monetising ecological and social consequences of implementing certain process steps or material streams. Due to the historical development of the ship dismantling industry as explained in section 2.1.2, it is anticipated that tangible insights in the economically added value of environmentally sound ship dismantling could provide substantiation for the potentially required surplus for ship owners or offtakers.

Considering the fact that approximating the monetary value related to process phases for the totality of an environmentally sound scrapping concept has not been performed, research on relatable topics has been investigated from two angles. Firstly, the accounting of environmental and social aspects within business valuation in general, and especially from the renewable energy sector (Zore et al., 2018), waste management (Sala-Garrido et al., 2023), and construction sector (Li et al., 2023). Secondly, monetising specific scrapping related process aspects within an environmentally sound concept (Jain, 2017). Also, the methodology of including the economic chain in the ecological chain through the Eco-Cost/Value Ratio will be touched upon.

[1]unspecified process phase

(Zore et al., 2018) uses the comprehensive approach of the Sustainable Net Present Value [SNPV] for optimising individual aspects of the renewable energy sector in relation to the investments required [i.e. which element of social, environmental, or economical within a specific renewable energy sector has the largest influence, and allows for optimisation]. Moreover, (Azapagic et al., 2016) has proven that it is important for future investments allowing for development that they are as optimal as possible [which is inconsistent and location-dependent] from the four-part sustainability, economic return, environmental efficiency, and social righteousness. Which aligns the purpose of the accounting methodology, as well as the goal for monetising the environmental and social aspects of a environmentally sound proposition. Moreover, a specific micro-economic variant of the SNPV, named the sustainability profit, is proposed in (Zore et al., 2017), including several case studies to proof its applicability on company level.

The construction waste valuation of non-market value placed the emphasise on the additional loss of natural resources due to a certain level of cost associated unwillingness to recycle [i.e. do the costs for using a landfill justify the incured additional costs from the loss of resources]. The methodology used for the research was only focused on the social level and did not include the ecological/environmental costs, and is therefor deemed too blunt for the purpose of this research. Furthermore, the used data has been acquired through an extensive survey. This method has been used in the past for research related to vessel scrapping by (M., 2010), but is rather time consuming and deemed less accurate than direct empirical estimations deduced from literature (Andersen et al., 2001), (Jain, 2017).

The methodology for approximating the shadow price of municipal waste as proposed in (Sala-Garrido et al., 2023) could be reflective for the purpose of this research, because the estimation is performed through a directional output distance function [i.e. multiple input/output function, with an adverse relation between the input and output, and based on separate variables], which does comprise the desired theoretical coverage for this research with regards to ecological/economical added value perspective. However, each unit under evaluation [i.e. a singular scrap process] would require a significant amount of input and output data. Since the availability, and reliability, of data is expected to be scarce, it has been decided that this methodology exceeds the purpose of this research.

Some research has been performed on added value and economic impact of supplementary processes included in technology-based vessel dismantling. An example is the plasma gasification unit for energy generation through the non-recyclable waste streams by (Jain, 2017). Here, the influence of a gasification unit in the proposal, with the aim to guarantee a level of self-sufficiency with regards to the required energy is investigated. This research will differ from (Jain, 2017) due to the fact that some assumptions and limitations will be more concrete in terms of costs, the material quantification as input will not be limited to one case study vessel but to different vessel types, and the proposal will be geographically specified in its potential. Moreover, (Jain, 2017) accounts only for the economic added value with respect to a green recycling yard, and neglects the indirect value with respect to adequate waste management and social value. Also, not all yard scenarios proposed are relevant for the case study maintained in this research due to the space requirements. The method proposed by (G.Vogtländer et al., 2000) has also been investigated. Despite the fact that some aspects on how to incorporate a multitude of chains into one are useful, the essence does not meet the goal of this research. Instead of translating the added value due to an ecological and social delta, (G.Vogtländer et al., 2000) includes the economic added value into the ecological indicator, thus the other way around.

In view of the elements stated as the potential success factors technology-based vessel dismantling, and the interest in the individual contribution of the each element per phase, it is logical to use a methodology that accounts for the influences separately. The SNPV methodology, specifically the sustainable profits applicable to micro-economic case studies, comprehends this most adequately. Furthermore, the case studies provided (Zore et al., 2017) elaborate on the usage and provide an extensive breakdown of how to include all aspects - including the ecological and social elements. The theory of the sustainable net present value, or SNPV, consists in principle of three elements. From the computation of these aspects, 4 different types of net present values can be composed. Which version of the NPV is selected, is mainly influenced by the stakeholders or decision-makers involved (Zore et al., 2018). Equation 3.1 and table 3.3 provide insight in the possible varieties of the NPV/sustainability profit, and how they are determined. For this research all contributing elements are deemed important, due to the origin of the global criticism, as explained in section 1.

$$NPV^X = w_a \cdot NPV^{econ} + w_b \cdot NPV^{eco} + w_c \cdot NPV^{soc}$$
$$\Delta SP^X = w_a \cdot \Delta P^{econ} + w_b \cdot \Delta P^{ecol} + w_c \cdot \Delta P^{soc} \tag{3.1}$$

**Table 3.3:** Net present value coefficients

| | Bearability NPV | Viability NPV | Equitability NPV | Sustainability NPV |
|---|---|---|---|---|
| $w_a$ | 0 | 1 | 1 | 1 |
| $w_b$ | 1 | 1 | 0 | 1 |
| $w_c$ | 1 | 0 | 1 | 1 |

The denominations for equation 3.1 are the economic contribution [$\Delta P^{econ}$], the ecological contribution [$\Delta P^{ecol}$], and the social contribution [$\Delta P^{soc}$]. The formula for determining the sustainability profit is visible in equation 3.2. Here, the implementation of the eco-costs elaborated on in subsection 3.5.1 can be found by the parameters $c_{i,t}^{R_{UNB}}$, $c_{j,t}^{S}$, $c_{i,t}^{R_B}$, $c_{j,t}^{P_B}$, and $c_s^{Comp}$. Further declaration of the variables is provided in table 3.4. The source for the eco-costs values will be ("Eco Costs Value", 2023).

$$\begin{aligned}\Delta SP &= \Delta P^{econ} + \Delta P^{ecol} + \Delta P^{soc}\\ &= \Delta R_t + \Delta R_t^{sub} - \Delta E_t - \Delta E_t^{ecotax} - I_t^{econ} - \Delta D_t^{econ} +\\ &\Big(\sum_{t\epsilon T}\sum_{i\epsilon R_T^{UNB}} \Delta q_{m_i}^{R_{UNB,consumed}} \cdot c_{i,t}^{R_{UNB}} + \sum_{t\epsilon T}\sum_{i\epsilon R_T^{UNB}} \Delta q_{m_j}^{P_{UNB,consumed}} \cdot f_j^{S/P_{UNB}} \cdot c_{j,t}^{S}\Big)\\ &-\Big(\sum_{t\epsilon T}\sum_{i\epsilon R_T^{B}} \Delta(q_{m_i}^{R_{B,tot}} - q_{m_i}^{R_{UNB,consumed}} \cdot c_{i,t}^{R_B}) + \sum_{t\epsilon T}\sum_{i\epsilon R_T^{B}} \Delta q_{m_j}^{P_B} \cdot c_{j,t}^{P_B}\Big) -\\ &\sum_{t\epsilon T} \Delta N_t^{jobs} \cdot c_s^{Comp}\end{aligned} \tag{3.2}$$

**Table 3.4:** Declaration of variables of equation 3.2

| Variable | Meaning | Variable | Meaning |
|---|---|---|---|
| $\Delta R_t$ | Revenues | $f_j^{S/P_{UNB}}$ | Substitution factor products |
| $\Delta R_t^{sub}$ | Subsidies | $c_{j,t}^{S}$ | Eco-costs coefficient |
| $\Delta E_t$ | Operational expenses | $\Delta q_{m_i}^{R_{B,tot}}$ | Waste material flow |
| $\Delta E_t^{ecotax}$ | Ecological taxes | $q_{m_i}^{R_{UNB,consumed}}$ | Used waste material flow |
| $I_t^{econ}$ | Investments | $c_{i,t}^{R_B}$ | Eco-costs coefficient |
| $\Delta D_t^{econ}$ | Depreciation | $\Delta q_{m_j}^{P_B}$ | Raw material flow |
| $\Delta q_{m_i}^{R_{UNB,consumed}}$ | Raw material flow | $c_{j,t}^{P_B}$ | Eco-costs coefficient |
| $c_{i,t}^{R_{UNB}}$ | Eco-costs coefficient | $\Delta N_t^{jobs}$ | New jobs |
| $\Delta q_{m_j}^{P_{UNB,consumed}}$ | Raw material flow | $c_s^{Comp}$ | Eco-costs coefficient |

## 3.6. Process Mapping

In section 3.4 an argumentation was made on the location of technology-based vessel dismantling on the process-product matrix, and the relevant KPIs for technology-based dismantling. The presented argumentation provides a grab on in deciding which process mapping methodology is most applicable to this process. The requirements for the mapping methodology is that individual added value [economical, ecological, and social] is the focus and visible in the overview. From this requirement, two different mapping techniques have been identified as potentially applicable. This section provides substantiation through purpose and relatable work for selecting the Sustainable Value Stream Mapping [SVSM] method. In the work of (Brown et al., 2014) three different [with respect to location on the process-product matrix] production processes have been analysed by means of Sustainable Value Stream Mapping [SVSM]. From this work insights have been gathered on data assembly, visualisation of process maps, and interpretations of results, and coupling sustainability indicators to value stream maps.

A parallel between scrapping and construction with respect to process mapping was found in (Ettema, 2021). Identifying process steps/decisions which could possibly allow for the reduction of environmental impact is accented in this work. The process mapping methodology used in (Ettema, 2021) is the Environmental Value Stream Map [E-VSM]. As stated in the proposal of (Garza-Reyes et al., 2018), this method distinguishes itself from VSM through a sixfold green waste implementation on the classical value stream map. The other method considered, the Sustainable Value Stream Map [SVSM], focuses on the sustainable added value of particular elements within the economic, environmental, and social domain. The fact that (Garza-Reyes et al., 2018) consist of an implementation justification for a new theory which has been cited regularly[2] implies an academic level of acceptance of the method. The six green wastes covered by the E-VSM could pose a fit for a circular scrapping concept evaluation consisting of energy, water, materials, garbage, transportation, and emissions. This indicates an overlap between the operational costs of interest for technology centred dismantling as elaborated on in section 3.4, and the green wastes included in the E-VSM.

However, the focus of this research with respect to the inclusion and mapping of the ecological, social and economic effect of sustainably sound dismantling is on the added value, and not potential green waste identification. Moreover, considering that the economical aspects are very accented within this research - the economical feasibility of technology-based dismantling define the most absolute definition of competitiveness - it is argued that the SVSM method is more applicable. Here, the decisive factor is the inclusion of the economic effect of certain non-economical aspects [social and environmental]. Both (Garza-Reyes et al., 2018) and (Brown et al., 2014) show that the required data is dependent on the identified KPIs. Since the decision-making on quantifying methods of impact indicators is linked to the KPIs, limited data gathering challenges are anticipated.

## 3.7. Comparison Scenarios

Establishing cases for both South Asia and Turkey on similar conditions and assumptions as for the selected environmentally sound scrapping process is essential for drawing conclusions with regards to the competitiveness. The scope of the research is discussed and substantiated in section 3.1. This scope needs to be translated to scenarios to create comparable grounds. Literary substantiation will serve as input for the process workings and material/waste quantification [sections 2.1.1, 3.3, and 3.4] and the single use carbon footprint and determination of the ecological and social consequences expressed by the eco-costs [section 3.5.1].

The scenarios comprise of the input, including potential vessel demobilisation from the designated area, the dismantling process, and the steel production process. The technology-based dismantling case consists of no demobilisation, dismantling through a technology-based concept, where the steel acts as feedstock for a local EAF steel production facility. This describes the technology-based dismantling concept as standard case study. The scope of three plausible scenarios for operational vessels in North Western Europe comprises of:

[2]85 publications on 23-05-2023

1. Demobilisation to South Asia. Here, the vessel is dismantled through a beaching process, where the gained steel acts as feedstock for a BOF steel production process [i.e. melting].
2. Demobilisation to Izmir, Turkey. Here, the vessel is dismantled through a landing process, where the gained steel acts as feedstock for an EAF steel production process - [*Turkey 1*].
3. No demobilisation, but dismantled through a technology-based dismantling concept in North West Europe. After dismantling the steel is transported by ship to Turkey, where it acts as feedstock for an EAF steel production process - [*Turkey 2*].

One of the distinguishing aspects of this research is the inclusion of transport for both its economical and ecological influence on the scrapping process. From the point of view of South Asia, useful data for approximating the impact of demobilisation has been performed by (Rahman et al., 2016). Literature applicable for creating an understanding of the process flow of South Asia and Turkey is (Rahman et al., 2016), (Steuer et al., 2021), and (Hiremath et al., 2015). Thereafter, estimations of the waste generated by conventional scrapping processes can be gathered by means of (Rahman and Kim, 2020), (Deshpande et al., 2013) and (Jain, 2017). The framework for linking the weight elements of vessels to the material quantification is selected and substantiated in section 3.3, and will be used for all geographical scenarios. The ecological and social impact analysis and the accessory economical delta realised by comparing the environmentally and socially [un]burdening impact of the standard case of technology-based dismantling compared to the conventional practices. The socially based criticism as explained in section 2.2.3 will have a more straight forwards approach for approximation since technology-based dismantling is less labour intensive, and will be practised conform European laws and standards. This implies EU labour conditions and salary, and no child labour.

## 3.8. Conclusion

The introduction of this chapter covered the bridge from the gap in academic work identified in chapter 2, to the requirements which are needed to eventually answer the main question of this thesis: What is the level of competitiveness of technology-based, environmentally sound vessel dismantling located in North West Europe? The structure proposed covers an approach for the analysis of the market dynamics which relates the designated geographical area to the technology-based dismantling process. The relevancy of the obtained fleet segment focus returns in the methodology selected for quantifying the material streams, and the vessel acquisition in the economic model. The material quantification of the identified potent feedstock for technology-based dismantling is then linked to the process analysis as input. Thereafter, from the process analysis and simulation the baseline of the economic model is constituted. The inclusion of the ecological and social costs of technology-based dismantling provides a threshold scenario compared to conventional dismantling processes. By means of using the Eco-costs and SNPV method for this, a single unit tangible outcome of the simulation is maintained. Through this an objective comparison can be made. The process mapping allows for a concise overview of which phases within technology-based dismantling provide a theoretically established added value. Eventually, sensitivity studies allow for monitoring the effect of adjustments originating from internal, process-related considerations, and externalities on the economic and operational performance of technology-based vessel dismantling.

# 4 Case Study Selection

In chapter 1 and 2 a breakdown of the conventional practices and the adverse consequences associated to these practices have been discussed. Section 2.3 provides an introduction to the emerging environmentally sound concepts, and initial insight in research dedicated to identifying relevant parameters for environmentally sound dismantling processes. This section will relate the emerging concepts to the research scope and presents a justification for which concept will be used as a case study for modelling technology-based dismantling concepts.

## 4.1. Decision-Making on Case Study

As stated in section 2.3, all technology-based dismantling facilities are conceptual at this stage, and none of these concepts are operational on a commercial scale. Examples of these concepts are *Elegant Exit Company*, *Leviathan GmbH*, *Atlas Decommissioning*, and *Circular Maritime Technology*. At present *Elegant Exit Company* and *Leviathan GmbH* are considered front runners, due to the acquisition of the vessel *Wan Hai 165* ("Wan Hai 165: From Approval to Action – EEC and ASRY's Ship Recycling in Motion", 2023), and reaching an agreement on yard usage ("Leviathan Plans Sustainable Ship Recycling Facility In Germany", 2023), respectively. As concluded in section 2.1.2, the vessel scrapping industry was cost-driven pushed towards developing countries with cheaper labour, whereas the business model of technology-based dismantling emphasises the investment costs and minimises operational expenses, including labour.

When relating the dismantling concepts to the scope as presented in section 3.1 the need for a comprehensive technology-based dismantling concept comes forward. Since the scope includes transport from the dismantling yard to the steel manufacturers, and demobilisation, the inclusion for transport in the dismantling concept is desired. Furthermore, the overall level of consideration with respect to the ecological footprint and waste management is deemed important. The reasons for this are the emphasise on the potential added value obtained through ecological and social unburdening, and the emphasise of the utility usage in the scope of the process. The social unburdening is covered by all potential concepts equally, since all concepts condemn child labour en occupational hazards of conventional dismantling practices. The ecological unburdening differs between concepts. The reason for this is that the treatment of the steel, before delivering it to the offtaker, and utility awareness is not included in all technology-based dismantling concepts. The treatment of steel is considered relevant for adequate waste management, due to the vast amount of paint and insulation on vessels. In section 3.4 it is argued that for the ecological footprint of the concept, it is important to include the effect of utility usage on the emission chain of the dismantling concept. This implies that a technology-based dismantling concept including steel treatment and their utility usage in their proposition is favoured as case study.

Currently, the concept with the most comprehensive approach for offering a conceptual solution to dismantling large volumes of vessels is *Circular Maritime Technology*. The company offers a start-to-finish concept including the dismantling of the vessel, separating and autonomously cleaning the material outflow, and smart transportation. This approach has a twofold working on the business case of technology-based dismantling. Firstly, the sequential set up of the concept allows for a theoretically achievable high throughput volume, with minimal human interference during dismantling. This aligns with recommendations made by (Andersen et al., 2001). Secondly, by enabling the transport of highly dens units of cleaned steel through an environmentally sound process, the product meets the demands for scrap steel quality and quantity set by the steel industry. Moreover, the theoretical operational set up of *CMT* scores high in terms of including the measurement parameters as displayed in figure 2.3, and provides a closed system operation reducing the risks of hazardous waste contamination. Summarising this, it is concluded that the technology-based dismantling concept of *CMT* is an adequate candidate for investigating the competitiveness of such concepts. By means of the sensitivity studies included in the scope of the research, the effect of operational and business model adjustment will be observed, generalising the simulation model.

## 4.2. Case Study Introduction

In essence the *CMT* concept utilises the dry dock concept [table 2.2, section 2.1.2] with a sophisticated process execution. The concept consists of several dismantling phases, with supporting facilities involved in the execution of the process. As stated in subsection 2.1.2, one of the most economically pressing aspects for environmentally sound vessel dismantling is coping with process related costs including proper waste management and labour costs in developed countries. The non-uniform ratification of these rules strengthens the position of the conventional scrapping powers. Therefore, the *CMT* concept relies heavily on [automated] machinery to minimise human interference. A general overview of the conceptual process as offered by *CMT* is provided in figure 4.1.

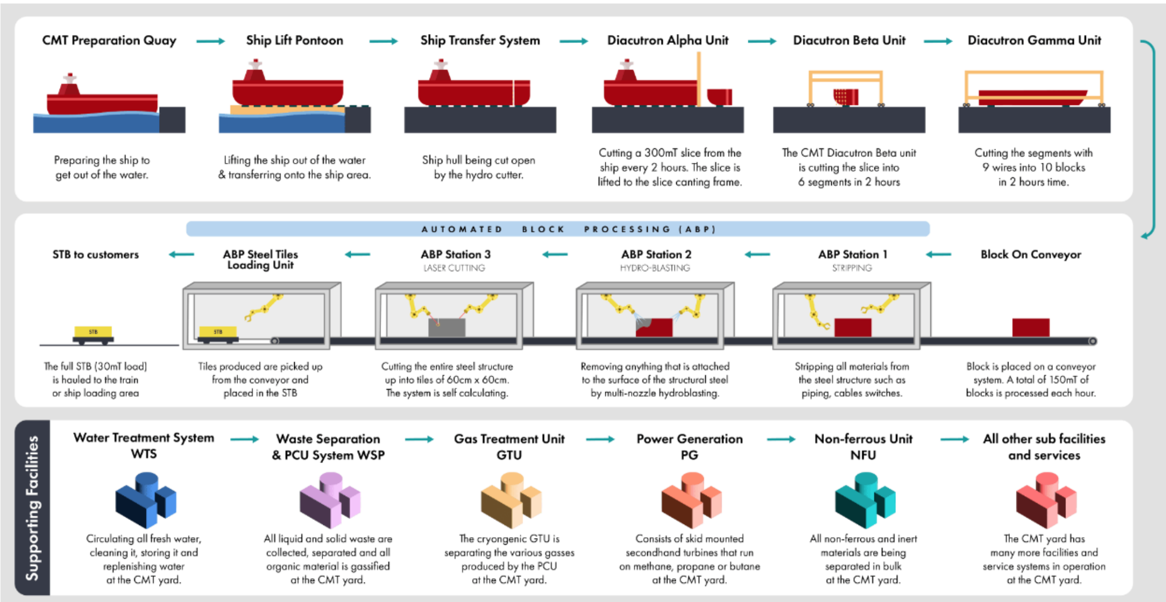
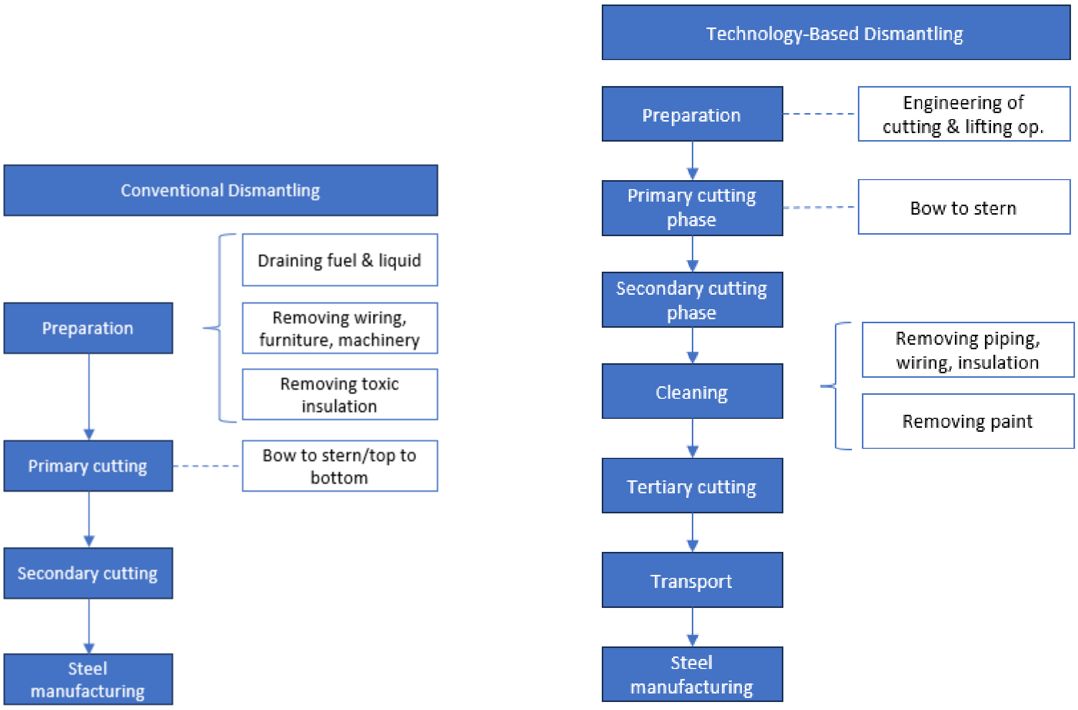



**Figure 4.1:** *CMT* process "The Dangers of Sea Pollution", 2023

The first step of the process is the engineering of the cutting process. Thereafter, the vessel is lifted out of the water by means of a lifting pontoon. A ship transfer system is used for getting the vessel in the designated cutting area. The cutting process is sequential, where a three-stage technological solution is used, named the *Diacutron*. The second phase consists of a fully automated block processing unit, where the blocks are cleaned and cut to sizes appropriate for the transport system. The supporting facilities comprise of digital and employee units, and direct process related units. The most important components for this research are the process related units, consisting of the water utility and treatment system including accessory piping, and the waste separation and pyrolysis unit.

When comparing figure 2.1 and figure 4.1 a great amount of process overlap can be identified. However, The sequence of some of the process phases are different. The difference in process sequence is highlighted by figure 4.2. Here, it can be seen that in essence the preparation and cutting of the conventional process are switched around, and performed by [automated] machinery.




**(a)** Conventional dismantling case

**(b)** Technology-based dismantling case

**Figure 4.2:** Process comparison of conventional and technology-based vessel dismantling

# 5 Results

## 5.1. Market Dynamics

One of the most important aspects of CAPEX intensive, technology-based vessel dismantling is achieving the demanded throughput volume within a certain time span, as emphasised in figure 2.2, in section 2.3. For the operational analysis to be successful, it is important to investigate which fleet segment poses an adequate feedstock for the envisioned throughput volume in tonnes. Therefore, the main purpose of this section is to investigated what the most suitable fleet segment for vessel dismantling in the designated region is, and how these segments are valued at end of life. This section will provide substantiation for selecting container ships, chemical tankers, multi purpose vessels, product tankers and general cargo vessels as the most feasible commercial class, all in the lower-end size class of the Handysize segment. Moreover, an explanation on the data-driven process of the acquisition price of these segments is proposed. The selection is proven through identifying the largest commercially active ports and sailing routes in the area, and linking this to the naturally berthing vessels. It is verified that the considered segments' fleet age and demolition age provide a statistical alignment for dismantling feasibility. Moreover, the designated commercial classes are linked to a size class, of which potential irregularities in demolition age have been ruled out. As elaborated on in chapter 3, the decision-making of this structure is a top-down feasibility study, where an adaptive interpretation of the first of Porter's Five Forces is used.

### 5.1.1. Relevant Ports & Commercial Segments

In terms of berthing and commodity transshipment, the largest ports in North West Europe are the Port of Rotterdam, the Port of Antwerp, and the Port of Hamburg ("10 major ports in Europe", 2021). The identification of which commercial class is most dominant in North West Europe is performed by means of the port calls. *Clarksons* data provided logs of the Port Calls including fleet type over the time span of 4 years [2019-2022]. Despite the fact that this time array covers the Covid-19 era, the insights in terms of commercial segments berthing are considered a good reflection. The reason for this is that these ports are driven by the locations' processing industries, and transshipment supply chain demand. The aggregated amount of port calls for North West Europe is visible in figure 5.1, while the calls per separate port are visible figures A.1 until A.3 in Appendix A.

From the cumulative breakdown can be concluded that the most dominantly present commercial fleet types are container ships, chemical tankers, Roll-on/Roll-off [Ro-Ro] vessels, Multipurpose [MPP] vessels, and General Cargo [GC] vessels. However, due to the nature of business of the Ro-Ro segment and the limited amount of service suppliers [5], combined with a lot of ferry characteristics implying several port calls per day ("RoRo: Roll-on Roll-off", n.d.), it was decided to use a form factor of 0.50 on the amount of Ro-Ro port calls to actual Ro-Ro vessels. Evidence supporting this decision was also found during the vessel size substantiation through *Marine Traffic* records. Therefore, the top 5 most relevant commercial segments resulted in discriminating the Ro-Ro segment and including the product tanker segment. Table 5.1 provides an insight in the amount of port calls per year during the investigated time span.

**Table 5.1:** Port calls breakdown

| Commercial Segment | Port of Rotterdam | Port of Antwerp | Port of Hamburg | Total | Annual average |
|---|---|---|---|---|---|
| Container ship | 21990 | 17316 | 13792 | 53098 | 13274 |
| Chemical Tanker | 19042 | 9752 | 2977 | 31771 | 7942 |
| MPP vessel | 11911 | 4320 | 3670 | 19901 | 4975 |
| Product tanker | 7271 | 4253 | 3167 | 14691 | 3672 |
| General Cargo | 7550 | 3536 | 2282 | 13368 | 3342 |

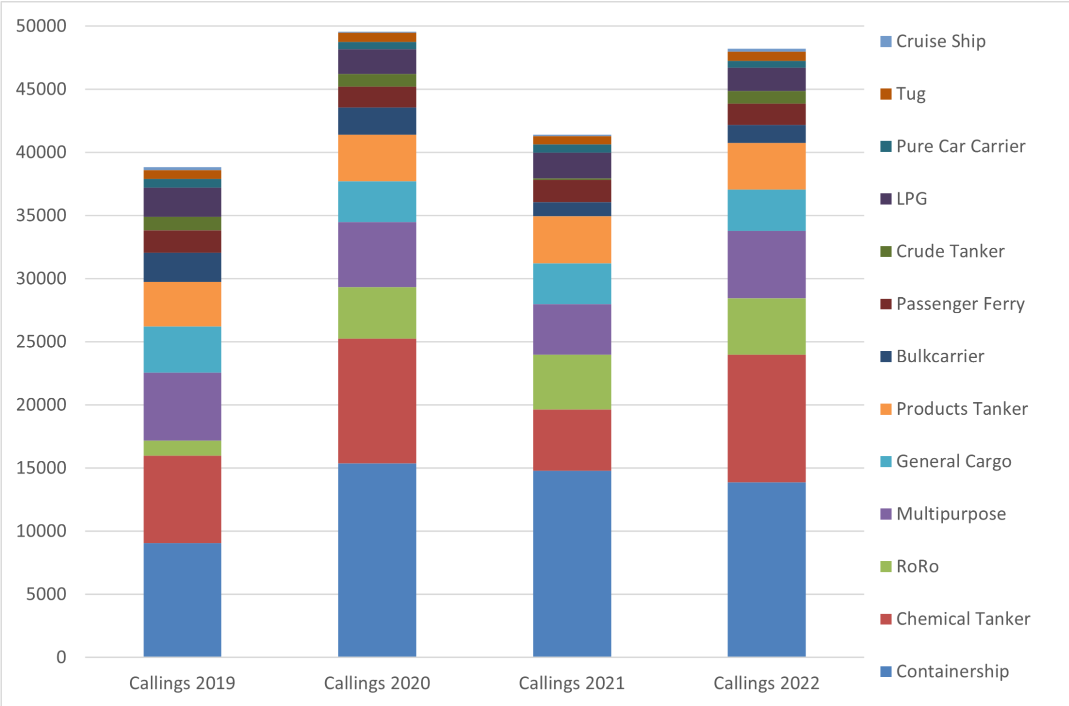



**Figure 5.1:** Aggregated port callings North West Europe

Through *Clarksons* data has been gathered to determine the dismantling potential of the selected commercial fleet, plotted against historical data of the dismantling age. For the segments as displayed in table 5.1 the nominally distributed fleet and scrap age is visible in figure 5.2. The data set consists of varying amounts of input in terms of vessels, especially for the dismantling age. This is caused by the non-transparency of the dismantling industry. To provide transparency on how the figure is acquired, the number of vessels used, the average ages, and standard deviations are provided in table 5.2.

From figure 5.2 can be deduced that there is significant difference in terms of dismantling age deviation between some of the commercial segments. The two most obvious, and contrary, segments are the container vessel fleet, and the GC vessel fleet. This can be related to the most common contracting methods for both vessel types [for container vessels contracts of affreightment for a specific cargo capacity - often on a set route [liner contract], and for GC vessels charter contracts[1]] ("Maritime Contracts", n.d.), (Dickie, 2014). This implies a certain level of predictability in terms of income, amortisation schemes, and costs for container vessel owners. On the other hand GC vessel owners are very dependent on day rates, thus it may be financially attractive to maintain older GC vessels. In general, the vessel size related to the demolition age is also of significance because of load induced fatigue (Fricke, 2017). Therefore, potential influence of the size-demolition age will be tested for the designated size class in section 5.1.2.

[1]Either day rate or time charter

**Table 5.2:** Fleet & dismantling age distribution [years]

| | Container ship | Chemical tanker | MPP vessel | Product tanker | General Cargo |
|---|---|---|---|---|---|
| Average fleet age | 16.20 | 16.75 | 20.11 | 14.49 | 37.46 |
| Average dismantling age | 25.73 | 27.42 | 28.60 | 30.70 | 39.49 |
| Standard deviation fleet age | 7.28 | 10.72 | 10.24 | 9.72 | 24.16 |
| Standard deviation dismantling age | 5.81 | 6.26 | 8.62 | 8.91 | 14.40 |
| $n_{fleet}$ | 5000 | 4138 | 3261 | 5000 | 5000 |
| $n_{dism}$ | 183 | 170 | 93 | 360 | 198 |

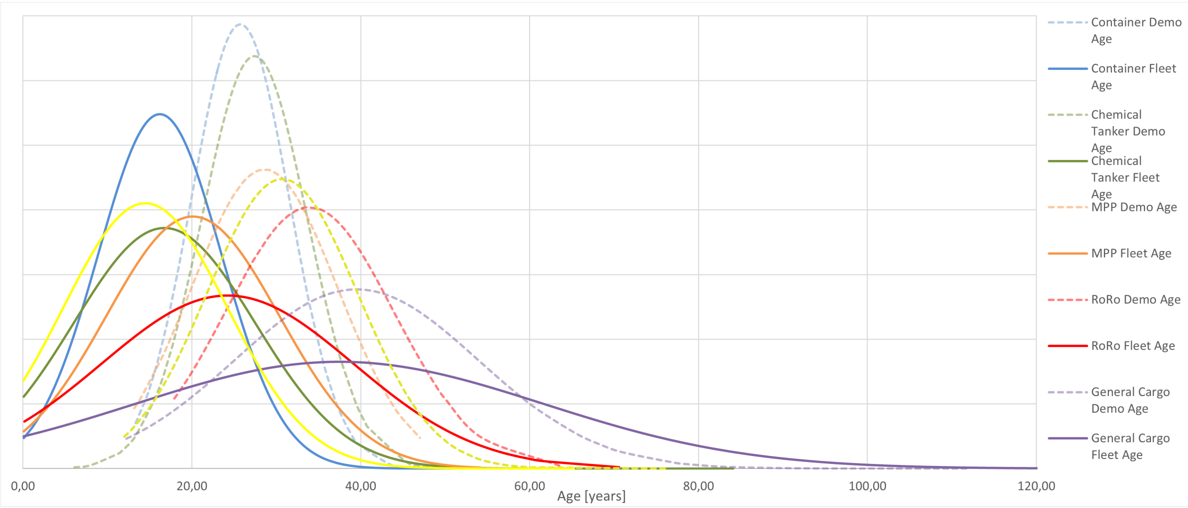



**Figure 5.2:** Fleet age plotted against historical dismantling age

Besides the obvious difference between certain markets in terms of predictability of the dismantling age, it is noticeable that the majority of the operational fleet is aged right before the average dismantling age. From this can be concluded that the selected commercial segments, derived from the port calls analysis pose a feasible short addressable market for dismantling parties. Therefore, the accessory size classes for the commercial segments included in table 5.1 and 5.2 must be identified.

### 5.1.2. Size Class & Age

Now that the commercial segments have been selected and analysed, the second step is to link this to the most potent commercial size. For this a complete data set[2] of port calls has been obtained through *Marine Traffic*. Considering the fact that the Port of Rotterdam is the largest port in terms of cargo handling and quay capacity, this port was selected for composing a $n = 30$ days data set. This decision does influence the reliability of the analysis as the Port of Rotterdam is skewed towards bulk transshipment when compared to the Port of Antwerp and the Port of Hamburg. Nevertheless, the commercial fleet selection has been based on all three ports. Since throughput volume is key for technology-based vessel dismantling, the port with the largest berthing quantity is considered the most relevant. For the randomly selected month[3] the relation between loading type and vessel size in terms of port calls is visible in table 5.3. As mentioned in section 3.2, the LDT is leading in determining the throughput volume, either obtained by many smaller vessels, or sufficient larger vessels. Data shortage on the Light Displacement Tonnage of the vessels berthing in the selected month obstructed providing insight in the accessory LDT quantity. Therefore, it is decided to provide the available DWT capacity of the vessels as an additional indicative measure for the cumulative dismantling capacity of the berthing vessels.

[2]With complete data set is referred to vessels' name, type of port call, destination/voyage origin, time spend in port & at leg, commercial segment & commercial size, and fleet type

[3]June 2023

**Table 5.3:** Port callings breakdown commercial size class - Port of Rotterdam

| Commercial size class | Wet bulk | | Container ships | | Dry break-bulk | | Dry bulk | |
|---|---|---|---|---|---|---|---|---|
| | Vessels | DWT capacity | Vessels | DWT capacity | Vessels | DWT capacity | Vessels | DWT capacity |
| Aframax/LR2 | 61 | 6,636,673 | 0 | 0 | 0 | 0 | 0 | 0 |
| Handymax/MR | 56 | 2,705,579 | 0 | 0 | 0 | 0 | 0 | 0 |
| Handysize | 1427 | 9,446,640 | 0 | 0 | 0 | 0 | 0 | 0 |
| Panamax/LR1 | 13 | 952,225 | 0 | 0 | 0 | 0 | 0 | 0 |
| Suezmax | 66 | 10,01,948 | 0 | 0 | 0 | 0 | 0 | 0 |
| VLCC/ULCC | 25 | 7,695,944 | 0 | 0 | 0 | 0 | 0 | 0 |
| Capesize | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 1,683,368 |
| Feeder | 0 | 0 | 2 | 35,784 | 0 | 0 | 0 | 0 |
| Panamax | 0 | 0 | 2 | 104,110 | 0 | 0 | 3 | 222,500 |
| Post Panamax | 0 | 0 | 0 | 0 | 0 | 0 | 12 | 1,013,555 |
| Small Feeder | 0 | 0 | 68 | 472,666 | 0 | 0 | 0 | 0 |
| ULCV | 0 | 0 | 2 | 309,400 | 0 | 0 | 0 | 0 |
| VLBC/ULBC | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 1,011,332 |

What is noticeable is the dominant presence of the Handysize segment for bulk carrying, and the small feeder dominance for container shipments. This is not surprising as the average vessel size port callings in the EU is around 7,000 GT ("Maritime freight and vessels statistics", 2022). Most commonly a Handysize vessel has a loading capacity between 15,000-35,000 DWT ("What is Handysize bulk carrier?", 2023). However, the definition in terms of loading capacity is non-existent. Other loading capacities found are 15,000-40,000 DWT ("Handysize", n.d.), and up to 50,000 DWT ("Handysize", 2022). Therefore, it has been decided to create a specific breakdown of the Handysize segment port calls, which is visible in figure 5.3. From this figure can be concluded that the lower-end of the Handysize segment is most dominant in the North West Europe sea trade. This can be explained through the facilitating role that the ports present in this region fulfil with respect to the downstream and hinterland trade. As visible, the most dominant size classes are between 2000 and 9000 DWT, where the designated wet bulk Handysize vessels have a slightly larger spread towards some larger size classes.

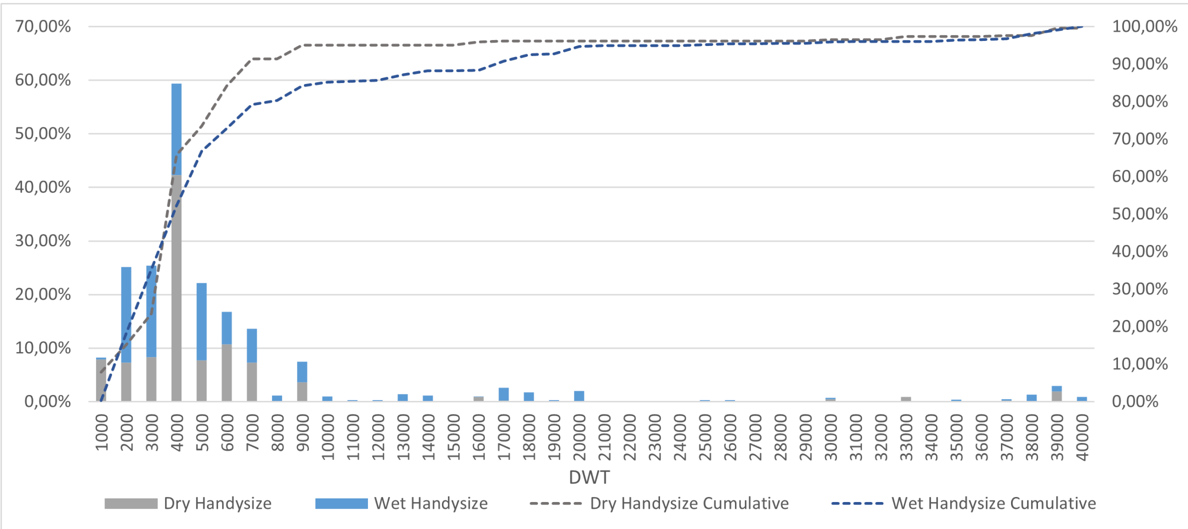



**Figure 5.3:** Handysize loading capacity breakdown Port of Rotterdam

The breakdowns presented resulted in the decision-making of focusing on the smaller vessels used for the transshipment business in the designated area. Through this decision the criteria for the availability of large throughput quantities on natural accretion per year is being met. However, the relation between fleet age and dismantling age has been taken on all available data, resulting in a varying LDT and DWT profile. Consequently, it is of importance to investigate if there are any deviations in dismantling age over the commercial size classes profile. This visualisation is visible in figure 5.4[4].

[4]The same data set as table 5.2 has been used

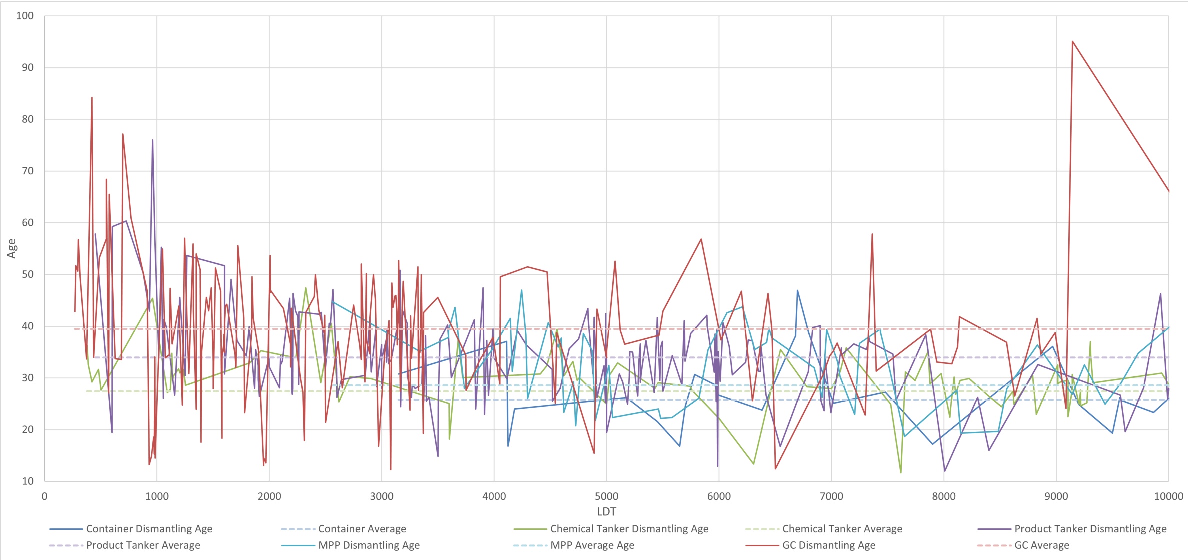



**Figure 5.4:** Dismantling age vessel size relation

As visible there are some slight outliers within the GC vessel segment, but in general there are no larger deviations in dismantling age for the relatively smaller size classes. Figure 5.4 displays only the LDT segment which complies with the Handysize and Small Feeder segments of interest following from table 5.1. For reference, the graph for the entire course of DWTs is attached in Appendix A. By means of *Clarksons*, time series were obtained containing historical dismantling data per month[5]. Local fluctuations over time can be made insightful by means of the data in table. These fluctuations can be traced back to fluctuations in commodity demand and thus transport demand aligning with the shipping cycle. The dismantling industry related to the vessel size is made insightful by means of table 5.4.

**Table 5.4:** Historical global commercial size to dismantling potential

| Commercial size class | Percentage/total quantity | Commercial size class | Percentage/total quantity |
|---|---|---|---|
| Container ship 100 - 2,999 TEU | 73.20% | MPP 200 - 349 TEU | 22.40% |
| Container ship 3,000 - 5,999 TEU | 25.77% | MPP 350 - 499 TEU | 19.17% |
| Container ship 6,000 - 7,999 TEU | 0.97% | MPP 500 - 749 TEU | 26.03% |
| Container ship 8,000 - 11,999 TEU | 0.06% | MPP 750 - 999 TEU | 8.27% |
| Container ship [TOT] | 1,746 | MPP [TOT] | 991 |
| | | | |
| Chemical Tanker Parcel[6] | 0.06% | Small Product Tanker <10,000 DWT | 28.58% |
| Chemical Tanker Parcel 1 - 9,999 DWT | 12.64% | Product Tanker 10,000+ DWT | 31.34% |
| Chemical Tanker Parcel 10,000+ DWT | 15.21% | Handysize 10,000 - 24,999 DWT | 6.60% |
| Chemical Tanker Parcel 10,000 - 19,999 DWT | 5.88% | Handysize 25,000 - 54,999 DWT | 20.30% |
| Chemical Tanker Parcel 20,000 - 29,999 DWT | 2.91% | MR 40,000 - 54,999 DWT | 8.73% |
| Chemical Tanker Parcel 30,000 - 39,999 DWT | 5.27% | Panamax 55,000 - 84,999 DWT | 2.65% |
| Chemical Tanker Parcel 40,000 - 49,999 DWT | 1.08% | Aframax 85,000 - 124,999 DWT | 1.79% |
| Chemical Bulk | 9.06% | Product Tanker [TOT] | 2,680 |
| Chemical Bulk 1 - 9,999 DWT | 3.31% | | |
| Chemical Bulk 10,000+ DWT | 5.75% | GC <5,000 DWT | 65.19% |
| Chemical Bulk 10,000 - 19,999 DWT | 3.11% | Small Bulker <5,000 DWT | 3.50% |
| Chemical Bulk 20,000 - 29,999 DWT | 1.08% | Small Bulker 5,000 - 9,999 DWT | 2.57% |
| Chemical Bulk 30,000 - 39,999 DWT | 0.74% | GC 5,000 - 7,499 DWT | 11.03% |
| Chemical Bulk 40,000 - 49,999 DWT | 0.81% | GC 7,500 - 9,999 DWT | 6.10% |
| Chemical Unknown | 5.07% | GC 10,000 - 14,999 DWT | 3.82% |
| Chemical Unknown 10,000+ DWT | 0.20% | 15,000 - 19,999 DWT | 5.96% |
| Chemical Tanker [TOT] | 1,479 | GC 20,000+ DWT | 1.36% |
| | | Combos <10,000 DWT | 0.46% |
| MPP 1,000+ TEU | 7.77% | GC [TOT] | 2,801 |
| MPP 100 - 199 TEU | 16.35% | | |

[5]from 2005 until 2023
[6]In case there is no DWT size quantification, this is unknown/not noted during dismantling.

As visible in table 5.4 there are some size classes governing the historical dismantling figures. The market distribution will likely change in the future due to the fact that the market heads to building ever bigger ships (“Review of Maritime Transport and Infrastructure 2021”, 2022), enlarging the fleet wedge that accommodates larger vessels. Relating this to the LDT capacity essential for the high throughput volume for technology-based dismantling, larger vessels have an upside compared to the vessels highlighted in table 5.4. However, as pointed out by table 5.1 and figure 5.3, larger vessels are not frequently berthing in North West Europe. This implies that for permanent productivity in dismantling larger vessels, the demobilisation advantage in valuation and ecological footprint could be lost due to local unavailability. Since most larger vessels are still in operation, it is logical that they are not included in current dismantling data. However, the number of transshipment hubs like the ports covered in section 5.1.2, will still require large numbers of the smaller size segments. Therefore, it can be concluded that there is a match between the natural berthing of size classes of the covered ports in historical and future context, and potent dismantling size segments. The fleet segment for finding data for the material quantification model covered in section 5.2, will be on the size classes as highlighted in table 5.4.

### 5.1.3. Valuation Strategy

This section will provide the approach used for determining the theoretical $\$/LDT$ of EoL vessels, for the designated commercial segments. This will be used in the economical model for compiling the acquisition costs for the dismantled vessels. The reference for the valuation will be based on the geographic locations of the labour-based dismantling yards, which aligns with the the comparison scenarios as described in section 3.7. The price equations have been obtained by means of creating and enlarging a data set including the name, type, demolition location, DWT, GT, LDT, demolition $\$/LDT$, demolition date, and age scrapped. This information was retrieved from *Clarksons*. From the raw data the opaque character of the dismantling industry became clearly noticeable. Especially, the EoL demolition $\$/LDT$ and the LDT were often missing in the data set. Also, the calculation of the demobilisation advantage as discussed in section 3.2 will be discussed in this section.

#### Price Determination and Data Set Enlargement

The regions of interest for the price determination are South Asia and Turkey. In South Asia, a distinction has been made between India, Bangladesh, and Pakistan. The *Clarksons* data provided an unsatisfactory quantity of vessel valuations, resulting in a too low reliability for the derived price equation. It was decided to investigate methods for enlarging the data set. The first method was by means of the quarterly publication of *Robin des Bois*. These publications cover changes in local regulation, accidents, vessels to-be-scrapped, and EoL valuation fluctuations. The weekly EoL $\$/LDT$ prices for all relevant regions have been gathered from 2018 - 2022[7]. This overview is visualised in Appendix A, figure A.5.

The overview shows local changes due to regulatory incentives, and the shipping cycle. Occurrences visible are periods where Pakistan mandated an import ban on oil tankers due to local pollution on the scrap beaches [early 2019], and the influence of Covid-19 on the container transport prices. This translated itself in an increase in steel demand as well as transport demand, resulting in a huge increments in EoL vessel value. Most importantly, this figure provides a weighted aggregate over time for EoL vessel valuation for South Asia and Turkey. The reliability of the *Robin des Bois* data has been checked by means of comparing it to validated values from *Clarksons* on several dates throughout the years. With minimal to zero deviation the valuations matched. Therefore, the *Robin des Bois* valuation was deemed reliable enough to use for enlarging the data set.

The second data enlargement technique consisted of a holistic approach. By means of using the interrelation of vessel design parameters, often used in ship design as covered in section 3.2, the number of vessels in the data set missing the LDT was minimised. The relation between known size parameters[8] and the LDT have been investigated. The most reliable plots in terms of coefficient of determination, the most common measure of how well a mathematical regression model fits a data set, was provided by means of the GT-LDT plot. The plots including the trend line and coefficient of determination are visible in Appendix A.

[7]At the time of establishing this valuation overview, the quarterly report of Q1 & Q2 2023 where not yet published
[8]Tonnage capacities DWT and GT

The contributions of the data enlargement techniques described above, and the total $n$-value for each commercial segment per region, is visible in 5.5. The data sets of all valuations are visible in Appendix A in figures A.11 until A.15. The equations obtained for the determination of the EoL acquisition price of a vessel with a certain LDT is visible in table 5.6. Here, $x$ represents the vessels' LDT as input.

**Table 5.5:** Valuation data set breakdown

| | Container ship | Chemical tanker | MPP vessel | Product tanker | General Cargo |
|---|---|---|---|---|---|
| *Clarksons* coverage[9] | 79 | 39 | 22 | 96 | 7 |
| *Clarksons* GT-LDT relation[10] | 0 | 1 | 1 | 0 | 2 |
| *Robin des Bois* valuation | 54 | 85 | 32 | 129 | 19 |
| Both the GT-LDT relation and *Robin des Bois* valuation | 1 | 16 | 15 | 78 | 65 |
| South Asia | 125 | 136 | 56 | 286 | 47 |
| Turkey | 9 | 5 | 14 | 17 | 46 |
| Total | 134 | 141 | 73 | 303 | 93 |

**Table 5.6:** End of life valuation equations

| | Container ship | Chemical tanker | MPP vessel | Product tanker | General Cargo |
|---|---|---|---|---|---|
| South Asia | $-0.0066 \cdot x^2 + 555.82 \cdot x - 645,995$ | $489.6 \cdot x + 294,890$ | $-0.0062 \cdot x^2 + 400.86 \cdot x + 222,918$ | $543.14 \cdot x - 136,465$ | $427.32 \cdot x + 45,663$ |
| $R^2$ | 0.8358 | 0.7197 | 0.8517 | 0.9161 | 0.9264 |
| Turkey | $-0.0011 \cdot x^2 + 210.43 \cdot x + 126,469$ | $-0.0052 \cdot x^2 + 495.10 \cdot x - 216,477$ | $-0.0108 \cdot x^2 + 325.63 \cdot x - 124,673$ | $-0.0106 \cdot x^2 + 378.68 \cdot x - 85,918$ | $-0.0084 \cdot x^2 + 268.41 \cdot x - 7,383$ |
| $R^2$ | 0.9719 | 0.9152 | 0.9697 | 0.9649 | 0.8810 |

### Demobilisation costs

The last element of the valuation strategy for EoL vessels is determining the competitive advantage of omitting the demobilisation associated costs. By acquiring naturally berthing vessels, the shipowners do not have to realise a demobilisation to Turkey or South Asia. Therefore, the costs associated with bunkering, crew, canal/lock fees, and insurances will come to an end. Since the amount of crew, canal/lock fees, and insurances are size, flag state, route and cargo dependent, the deviation between the amounts accounted for these factors is considered relatively high. Therefore, it has been decided to exclude the non-emission related factors from the demobilisation costs approximation. As stated in section 3.2, the bunker costs can be obtained by means of the propulsion train calculation as proposed in (Woud and Stapersma, 2016). For this calculation the marine components installed in the case study vessels used for the material quantification model will be used. These vessels will be presented in section 5.2.

For approximating the required bunker quantity some parameters needed to be determined. For the vessel speed the design speed as obtained by (Papanikolaou, 2014)[11] was determined. The route and the accessory duration of the route at the set design speed have been determined through the distance-speed relation. The selected routes are visible in figure 5.5. Furthermore, engine suppliers data [SFOC, installed power], route distance, and the bunker price in Rotterdam had to be gathered[12]. The reason for choosing the design speed is that the required power [expressed in RPM] from the engine is plotted for optimal performance at 85% MCR within the engine envelope during design. Therefore, this provides the most reliable approximation. All engines have been taken into account, including the installed [shaft] generators. However, for the product tanker the installed auxiliary engines for the cargo pumps, tank heating and tank venting have been excluded from the calculation. After obtaining all relevant information, equation 5.1 has been used to determine the demobilisation bunker quantity and costs. Lastly, the cost is calculated to $\$/LDT$, allowing it to be accounted for in the acquisition price of the vessels.

$$Q_{bunker} = P_{ME} \cdot sfoc_{ME} \cdot t_{travel} \cdot N_{ME} + P_{AE} \cdot sfoc_{AE} \cdot t_{travel} \cdot N_{AE} \tag{5.1}$$

[9]Coverage indicates all relevant parameters are extracted from *Clarksons* only [LDT & $\$/LDT$]
[10]With a *Clarksons* known $\$/LDT$
[11]The DWT - design speed relation has been used for the determination
[12]OEMs involved in the case studies are ABC, MaK, Volvo & CAT

**Table 5.7:** Demobilisation Advantages

| | Container ship | Chemical tanker | MPP vessel | Product tanker | General Cargo |
|---|---|---|---|---|---|
| South Asia [$/LDT] | 70.74 | X[13] | 69.87 | 79.56 | 61.64 |
| Turkey [$/LDT] | 33.66 | X | 33.13 | 37.85 | 29.30 |

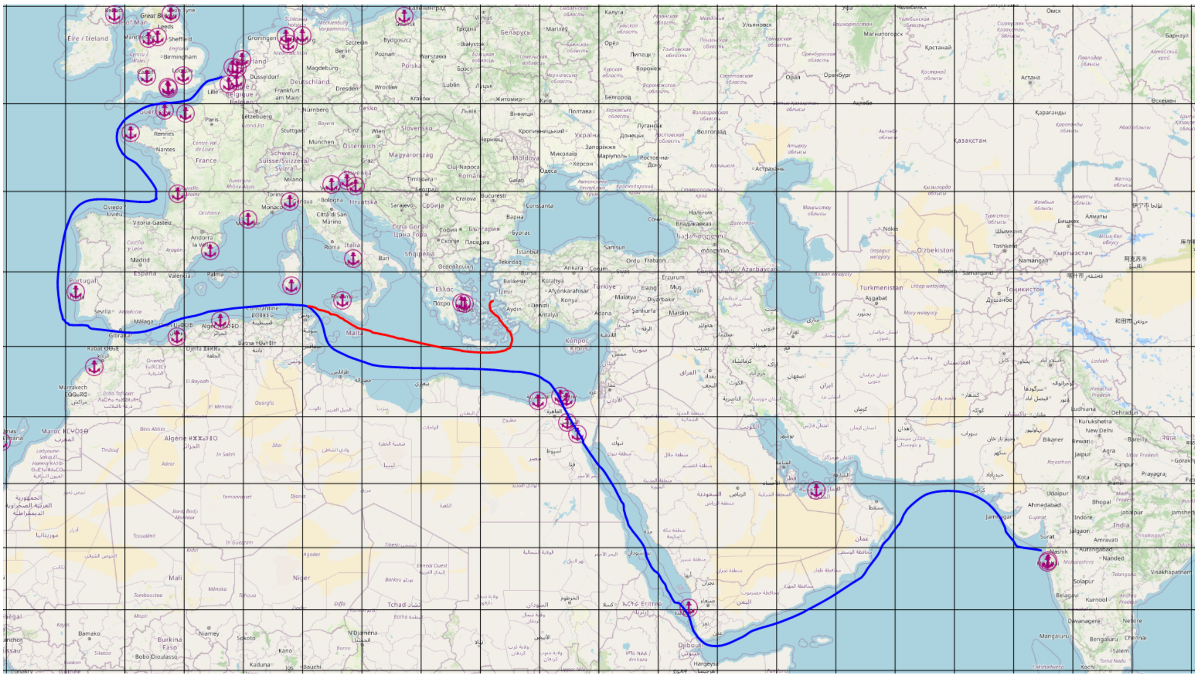


**Figure 5.5:** Demobilisation routes

### 5.1.4. Conclusion

The main purpose of this section was to investigated what the most suitable fleet segment for vessel dismantling in the designated region is, and how these segments are valued at end of life. In order to answer this question an analysis of the representative ports in North West Europe was performed, showing the transshipment hub character, combined with a large local [petro]chemical industry. This translates itself to a designated berthing fleet, servicing these commercial activities. The most common, unique port callings can be placed under the container ships, chemical tankers, MPP vessels, product tankers, and GC vessels. It could be concluded from the normally distributed current global fleet age and demolition age that the commercial segments highlighted by the port callings provide a potent feedstock potential for dismantling activities. Through relating the commercial segments to size classes, the transshipment purpose of the ports was emphasised again. The main focus in terms of size can be found in the container feeders, and the lower-end Handysize segment. An additional audit has been performed on the feedstock potential with respect to the dismantling age of these smaller size classes, in which could be concluded that there are no significant deviations in dismantling age. Only designated commercial segment deviation were observed, which can be explained through the contracting type. Historically, the narrowed down scope of commercial segments and size also scores high in terms of global dismantling offset. Here, a discussion has been added to highlight the expectations on the increasing dimensions of newbuild vessels, and its effect on potential dismantling feedstock. These substantiations resulted in identifying the suitable fleet segment for which the material quantification must be determined. Lastly, the valuation strategy for the commercial segments has been investigated. This will be the input for the economic model for the acquisition costs of the vessels. Also, the approach for determining the competitive advantage with respect to the demobilisation costs is explained. For the valuation strategy the emphasise is placed on the methodologies used to enlarge the available data set, through which accuracy for the valuation equations for the designated segments is ensured.

[13]See section 5.2

## 5.2. Material Quantification

The goal of this section is to establish an understanding of the material streams constituting dismantled vessels, which will be used as input for the process analysis. As explained in section 3.3, the transformation format from weight categories to material streams proposed by (Jain, 2017) will be used as a tool for understanding the process input. However, (Jain, 2017) used academic works to substantiate the distribution of certain weight categories to certain material classes [e.g. the outfitting elements]. For this research ship builders weight lists, used for stability calculations, were obtained. This connects with the the approach of vessel sampling for material quantification as proposed by (Andersen et al., 1999) and maintained by (Jain, 2017), but the level of detail as presented in the obtained weight lists is much higher. Therefore, it is argued that the complete weight breakdown as visible in Appendix B is a more accurate conversion tool from weight classes to material streams, allowing for accurate process input.

### 5.2.1. Vessel Selection

The first step was to complement the existing elements [e.g. M01 Machinery Piping] with the adequate weight codes used by the ship builder. Secondly, the conversion tool, from now on referred to as the transformation matrix, needed to drafted and substantiated. This transformation matrix distributes all weight codes to the materials the items consist of. For this both the actual weight lists, which also provided detailed material quantification [e.g. the amount of copper piping] as well as (Andersen et al., 1999), (Andersen et al., 2001), and (Jain, 2017) have been used. Lastly, the pricing for each material stream must be substantiated. The pricing used is based on the monthly steel scrap prices of Germany ("Metal Price Monitor 2022 - RETRALOG®", n.d.), since this provides more stability than the daily fluctuating prices of the Dutch scrap market. Table 5.8 provides an overview of the vessels used for establishing insight in the material structure of vessels. Since this is confidential information for shipbuilders, the actual lightship weights will not be presented in this report. However, all calculations have been performed with the actual numbers and are known by the author. Unfortunately, the search for a ship builders weight lists of a chemical tanker case study was unsuccessful. For the container ship, product tanker, MPP vessel, and GC vessel adequate case studies were found in the selected commercial size classes.

**Table 5.8:** Vessel overview

| Commercial segment | Loading Capacity | Dimensions [$L \cdot B \cdot T$] [m] | Specials[14] | Example vessel |
|---|---|---|---|---|
| Container ship | 788 TEU | $140 \cdot 21.8 \cdot 7.33$ | - | *Samskip Endeavour* |
| MPP vessel | 8200 t/10,795 $m^3$ | $118.14 \cdot 15.90 \cdot 7.21$ | geared [2 cranes] | *Beauforte* |
| Product tanker | 7,000 t | $109.9 \cdot 17.0 \cdot 7.0$ | cargo tank heating, cleaning & venting | *King Fisher* |
| General Cargo | 3800 t/5,250 $m^3$ | $89.7 \cdot 12.5 \cdot 5.48$ | - | *Baltic Fin* |

### 5.2.2. Results

A breakdown of the items placed under the categories as proposed by (Jain, 2017) is shown in table B.1 until B.5 in Appendix B. The outcome of the material quantification model, used as input for the process analysis and basis of the economic model, is visible in table 5.9.

**Table 5.9:** Material quantification result - mass percentage

| | Ferrous | Non-ferrous | Machinery | Electrical & electronic equip. | Minerals | Plastics | Liquids, chemicals & gasses | Joinery | Miscellaneous |
|---|---|---|---|---|---|---|---|---|---|
| **Container ship** | 88.64% | 1.34% | 5.89% | 0.48% | 0.03% | 0.66% | 0.25% | 1.74% | 0.95% |
| **Product tanker** | 83.17% | 1.82% | 7.23% | 0.25% | 0.02% | 1.65% | 0.61% | 3.07% | 2.18% |
| **MPP vessel** | 86.89% | 1.52% | 7.02% | 0.20% | 1.41% | 0.42% | 0.25% | 1.74% | 0.54% |
| **GC vessel** | 86.74% | 1.85% | 3.89% | 0.42% | 1.74% | 1.13% | 0.86% | 2.20% | 1.16% |

[14] Examples of specials are cranes, tank heating, etc.

## 5.3. Process Analysis

The process analysis discussed in this section comprises of a simulation of a technology-based dismantling concept, where *CMT* is taken as a case study. The aim of this section is to investigate all phases, and their dependency, in order to determine the key operational-economic parameters for technology-based dismantling. In this analysis additional emphasise is put on the throughput maximisation, energy consumption, and utility usage due to the dominant influence on the economic and ecological added value and costs compared to the conventional practices in South Asia and Turkey. Besides their dominant influence on the operational success, these parameters [in]directly align with the green wastes implementation of the E-VSM, as discussed in section 3.6. Despite that this methodology is not selected as the process mapping tool which will be used in section 5.5, the decision-making for translating the green wastes to the social, ecological, and economic impacts rests on ensuring a reliable scope of the process related added values and costs. The congestion points of the process have been identified from which an optimal cutting time is derived. This is a size-dependent calculation, where the total lead time equals about 1.5 to 4.5 days, depending on the vessel type. For this calculation several process factors are included such as the maximum slice/block size of the initial cutting processes, the operational time per day, the replacement time and quantity of saws per year, and the cutting losses generated by the saws. The level of self sufficiency in terms of energy depends on the quantity of material suitable as feedstock for the pyrolysis process. It is found that the power-to-need percentage is about 12% to 23%, depending on the vessel type. Understanding of the required process water for cooling and hydro blasting includes investigating the implications of the process water replenishment on the business model. The simulation model created allows for sensitivity studies, which are discussed in section 5.6.

### 5.3.1. Cutting and processing

The case study taken as the red thread for modelling technology-based dismantling is the *CMT* process as described in section 4.2. The vessel processing consists of 3 phases: the preparation, the cutting process, and the block processing. Besides the main processes the supporting facilities as discussed in section 4.2 have also been modelled. The facilities which are included are the pyrolysis unit allowing for a degree of self sufficiency, and all wet streams handling. All other operation supporting services are included for approximating the associated CAPEX, OPEX and electrical power demand [e.g. office buildings]. However, accounting for them on operational terms does not provide added value to the model, due to their supporting nature in the process.

The first step was to identify the sequential process steps and bottlenecks. Congestion within the process takes place when a certain process step cannot take place until the previous step is completed entirely. Within the process of *CMT*, two bottlenecks have been identified. The first one is between the transfer and the first cutting step [Alpha] of the vessel. The second one is between the last cutting step [Gamma], and the start of block processing. By means of equation 5.2 the total time per first slice [Alpha] of vessels can be calculated, through time approximations of all individual process steps provided by the technology suppliers through *CMT*, assimilated in table 5.10. An important assumption for the calculation of the time per block is that the yard of the dismantling concept features enough berths for engineering to be a continuous and simultaneous process in itself. Iterations including this step as part of the preparations phase proved that engineering as a separate procedure where multiple assets are simultaneously prepared is a hard prerequisite for operational and economical viability. Another important assumption is that the concept receives a 24-hour operating permit. This is important in terms of annual throughput as well as electric power demand [startup of the operation requires an additional power intake, which will be discussed in more detail in section 5.3.2].

$$t_{block} = \frac{t_{prep} + t_{\Delta prep} \cdot (n-1)}{n} + \frac{t_{cut} + t_{\Delta cut} \cdot (n-1)}{n} + \frac{t_{processing} + t_{\Delta processing} \cdot (n-1)}{n} \tag{5.2}$$

**Table 5.10:** Time steps overview

| Process step | Time [hr] |
|---|---|
| Preparation & engineering | 336 |
| Lifting operation | 4 |
| Transfer | 4 |
| Alpha cut | 2 |
| Lifting operation | 0.5 |
| Beta cut | 2 |
| Gamma cut | 2 |
| Stripping | 0.25 |
| Hydro blasting | 0.25 |
| Laser cutting | 0.25 |
| Loading unit | 0.25 |
| Warehouse transport | 0.083 |

During the simulations it became clear that the economical result of the operation is much dependent on the selected weight of the slices after the first cutting step. Since the weight of the slice is a selected parameter, several simulations for different weight steps have been performed. During these simulations larger slices provided a higher economic viability. This implies that designing the processing steps after all the cutting steps for a large weight capability results in better economic performance. The required lifting capacity after the first cut [Alpha] must be matched to this weight. However, the size and weight of the slice is constraint by the maximum capability of the downstream technology. Moreover, the key operational parameter with respect to the overall process is maximum throughput and minimal lead time. Equation 5.2 provides a trend for the required time per slice, which converges to a certain minimal time following the Markov Convergence Theorem. Therefore, the iterative process of simulating multiple slice weights is used to optimise the slice processing time for each commercial segment. The result is visualised in figure 5.6, from which can be concluded that the slice processing of all commercial segments is located near the Pareto optimum for the eventually selected weight. Adjustments in weight proved that increasing or decreasing the weight of the first slice results in a decrease in operational efficiency [i.e. move up the line or down the line, respectively]. This would result in a higher quantity of time per first slice, or more blocks at a constraint processing time.

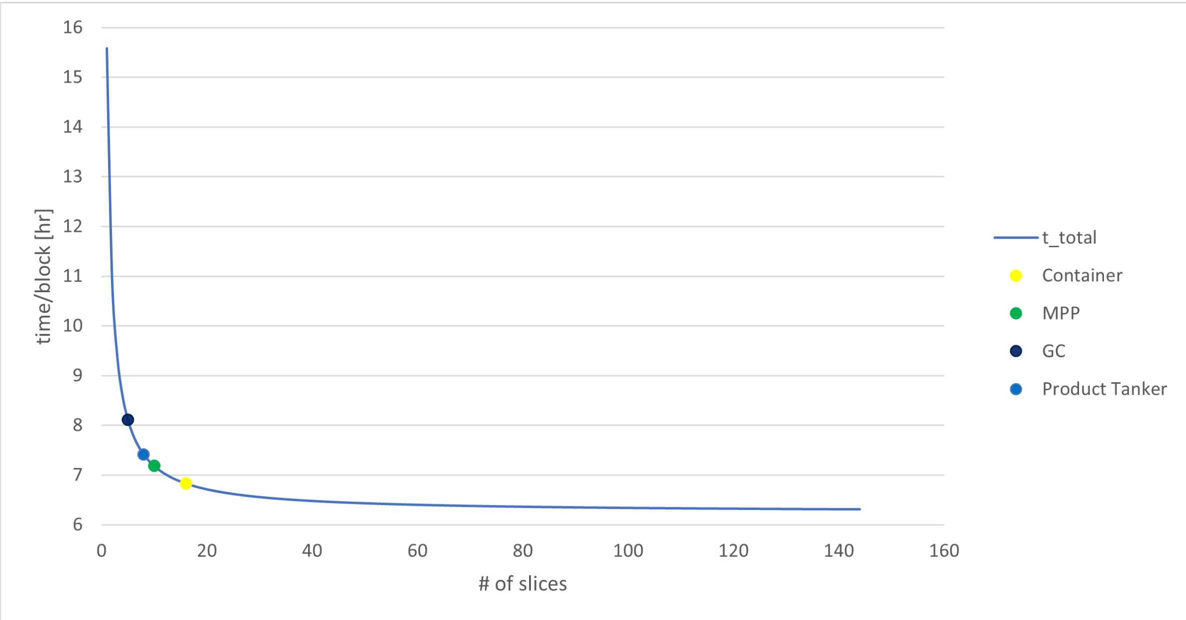



**Figure 5.6:** Time per slice handling

From the lightship of the vessels, the set weight per slice, and the accessory total processing time per slice, the lead time per vessel type can be obtained. Under the condition of setting an operational up time [97%], the annual throughput can be calculated. This is relevant from an operational point of view, as well as from a financing and economical point of view. From the aspired OEM of the saws, the lead time as displayed by table 5.10 is obtained. This is deemed achievable under the presumption that vibrations caused by the saw motions, as well as resonance caused by vibrations of the structure is kept to a minimum by retaining structural strength of the vessel. This could be effectuated by means of holding the slice tightly to the structure with the heavy lifting cranes used for the after-cutting lifting operation. Furthermore, it is assumed that all annual operational downtime [taken at 3% per year] is dedicated to routine inspections and maintenance, and replacing worn saws of the cutting stations. This results in about 12 minutes per saw replacement, which is deemed achievable as long as the saw replacement aspect is prioritised by the OEM in the design of the saw. Potential saw snapping has not been included in the simulation, because of the unpredictable nature of this event. Moreover, through the wear time, a prognosis of the annual amount of saws can be determined. By means of an average price estimation [saws differ in length, so presumably also costs] the annual OPEX with respect to saw replacement can be determined.

The cutting losses caused by the sawing steps have been calculated by means of the the saw width [50 mm] and the circumference of the vessels, including the structural parts. Considering the amount of slices from the case study vessels [5 for a GC vessel, and 16 for a container feeder], the cutting loss is estimated to be 0.20%-0.35% of the LDT of the vessel. The variation depends on the type, dimensions and structure of the vessels. However, the cutting losses will be included in the process water. The process water is treated where the materials filtered out are feedstock for the pyrolysis unit [PCU]. Since the regain percentage of steel before or after the PCU is assumed to be 100% [steel can easily be gathered by means of a magnet], it has been decided not to simulate the cutting losses explicitly.

### 5.3.2. Energy consumption

The energy consumption is one of the most crucial operational expenses of a technology-based dismantling concept. The used energy only has an indirect added value to the output products and is pure cash out. First, the approximation of the energy demand on daily and annual basis will be explained, after which the modelling and inclusion of the pyrolysis unit in the energy demand will be elaborated on.

The energy demand profile consists of the sum of numerous machines all requesting a different peak load. For the technology-based dismantling case study, estimations of the peak loads were obtained via the suppliers and developers of the technologies. The energy demanding phases and machines have been allocated to 26 energy categories - related to phases and supporting facilities of the concept. By means of the cutting time throughput and therefor machinery load, the average daily operational working time per category has been determined. The load factor for the operation is taken at 85%, equalling the design load factor for [chemical] plants (Leyton, 2016). Thereafter, equation 5.3 is used to determine the nominal load of each category and the entire cumulative load of the concept. The pricing for electricity is based on Dutch industrial purchase levels, where peak power load is the largest wedge of the fee (ACM, 2023).

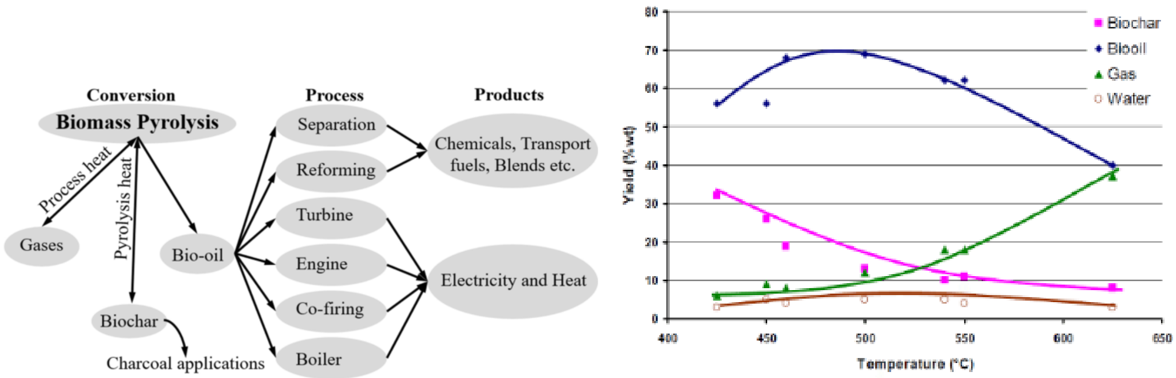
Considering the difference in annual throughput per commercial segment, the operational daily working time of the concept has been specified per commercial segment. Related to the dismantling operation, this is especially of importance for the different energy requirements generated in bottleneck steps of the process [i.e. caused by the differing amount of vessel throughput per time span]. The daily operational time has been determined by means of the annual operational capacity [time], constraint by the amounted annual throughput. The yard lights are only on during the night, so 12 hours is taken for this. All other categories are considered continuously operational. This way the accuracy of the prognosis in terms of energy demand is guaranteed. For the determination of the power demand of all categories, additional redundancies for energy intense process steps have been taken into account in the peak demand.

$$P_{nom} = LF \cdot P_{peak} \tag{5.3}$$

Since the used energy only has an indirect added value to the output products, creating as much independence from purchasing energy and becoming more self reliant could be a sensible investment. One of the possibilities of doing this is by means of including a pyrolysis unit [PCU] in which waste streams of the vessels can act as feedstock. For the simulation of including a pyrolysis unit a two-step biomass PCU has been modelled, where a distinction is made in terms of wet and dry feedstock. Table 5.8 in section 5.2 provides the material output streams of the vessels. The streams applicable as feedstock for pyrolysis consist of the non-metallic streams of the vessel. These streams are the *Joinery*, *minerals*, *plastics*, *liquids*, *chemicals & gasses*, and *miscellaneous* [i.e. paint]. It is plausible that residual fuel in the bunker tanks is present. However, this is a case-by-case quantity that owners presumably try to minimise. Therefore, this parameter is assumed negligible, and not included in the PCU feedstock. A two-step PCU refers to a two-level temperature reaching point. The first level stimulates the feedstock to turn from solid in to oily and reaches a temperature of around 450 $^\circ C$, and the second step turns the feedstock from oily into gas and reaches a temperature of about 850 $^\circ C$. The output products are hydrocarbon gasses, which can be used as fuel for gas generators, and ash & carbon black which can be sold to concrete manufacturers.

Figure 5.7 provide insight in the process streams and efficiencies of a bio mass feedstock based PCU. As visible in 5.7b, the mass percentages obtained at high temperature [beyond the temperature included in the x-axis is the condensation temperature array] for bio oil and gas converges to about 40% each. However, several elements have a dominant influence on the workings and efficiency of the pyrolysis process. The most influential parameters are moisture level and uniformity of feedstock (Jahirul and Rasul, 2012). Since the material streams that will act as feedstock consist of a cluster of materials and are partly wet due to the process water, the thermal efficiency of the PCU is taken conservatively at 25%. Furthermore, for the simulation it is assumed that the streams required for the PCU are uniformly supplied to the PCU in terms of quantity per time.

Besides the thermal efficiency of the pyrolysis process, the gas generators efficiency must be determined. It is assumed that the waste heat of the generators is regained and can be made useful [e.g. PCU feedstock drying], resulting in a relatively high efficiency of 95% [15]. From the input as prescribed by this section and table 5.9, a certain level of electrical power independence is realised. This is referred to in table 5.9 as the produced power-to-need% per vessel type.




**(a)** PCU streams

**(b)** PCU efficiency with biomass feedstock

**Figure 5.7:** PCU workings & efficiencies

**Table 5.11:** PCU results

| | Container ship | Product tanker | MPP vessel | GC vessel |
|---|---|---|---|---|
| Day-based production [kWh] | 30,072 | 54,929 | 33,739 | 47,871 |
| Process start up [kWh/year][16] | 2.04 | 2.04 | 2.04 | 2.04 |
| Annual production [kWh] | 10,645,488 | 19,444,856 | 11,943,490 | 16,946,319 |
| Power-to-need [%] | 12.3% | 22.5% | 13.8% | 19.5% |

[15]This efficiency has been achieved in the USA by Caterpillar

### 5.3.3. Process water consumption

The process water of the facility is a fundamental element of the operation. The water streams consisting of process water, water draining & treatment, a black water stream, and sludge processing make the sawing and hydro blasting possible. The facilities are of importance, because of the indirect added value in guaranteeing adequate waste management and required process cooling.

The daily required quantity of process water is estimated to be 240,000 $m^3$, based on the cooling requirements of the saws and the hydro blasting demand. For the simulation all required process water streams have been assigned a factor for their water demand. The Alpha, Beta, and Gamma cutting machinery were all assigned the factor equal to the amount of saws. Hydro blasting is not uncommon within the ship repair industry. Therefore, accurate approximations of the flow rate required for the hydro blasting processing units could be obtained via OEMs. It has been assumed that a flow rate of 60 $L/min$ at a pressure of 950 Bar suffices for paint and adhesive cleaning in the hydro blasting unit ("PressureJet - Manufacturer Of High Pressure Hydro Test Pump, Hydro Jetting Machine & High Pressure Cleaning Pump", n.d.). With four operational lines for block processing, that would equal a daily water usage of 345,600 L, or about 350 $m^3$. The process water usage factor for the hydro blasting in total then equals 0.022[17].

It is assumed that due to water loss caused by friction of the saw and in the PCU process, around 4% on a daily operation is evaporated. The replenishment of this water is crucial for a smooth operation, and must be accounted for in the operational expenses. For the pricing the tariffs of Dutch water companies for large offtakers have been taken. The total annual amount of required replenishment equals around 3.4 million $m^3$. Besides the water cycle active in the technology-based dismantling concept, also large quantities of electricity is required for the pumps and filtration units. These have all been accounted for in the electricity establishment. Moreover, expressed per ton of processed vessel, the water and electricity quantities are visible in the sustainable value stream map, discussed in section 5.5.

### 5.3.4. Conclusion

In this section the goal was to define and investigate all process phases to determine the key operational-economic parameters for technology-based dismantling. For this a simulation model was designed where *CMT* acted as a case study. The throughput maximisation requirements, energy consumption, and utility usage were accented in the composition of the simulation model. The reason for this is to ensure a reliable, academic scope of the process related added values and costs due to their dominant influence on the economic and ecological performance. The identified congestion points resulted in deriving an optimal cutting time based on the technology capacities. This size-dependent calculation resulted in total lead times of about 1.5 to 4.5 days, depending on the vessel type. For this calculation several process factors are included such as the maximum slice/block size of the initial cutting processes, the operational time per day, the replacement time and quantity of saws per year, and the cutting losses generated by the saws. The level of self sufficiency in terms of energy depends on the quantity of material applicable to the pyrolysis process. It is found that the power-to-need percentage is about 12% to 23%, depending on the vessel type. Understanding of the required process water for cooling and hydro blasting includes investigating the implications of the process water replenishment on the business model. Aligning with the structure and scope presented in figure 3.1, these findings enable calculating the process associated ecological and social impacts, and the overall simulation will provide the required input for the economic model.

## 5.4. Ecological, Social and Economic Analysis

The objective of this section is to determine the ecological, social and economic impact of technology-based dismantling, and measure how technology-based dismantling compares to the conventional practices from a single unit perspective. The approach followed for establishing the impact in a single unit way is by means of the eco-costs and sustainability profit, as explained in section 3.5. The results are expressed as the difference between the case study outcome and the comparison scenarios as discussed in section 3.7. It is found that the inclusion of both the ecological and the social contribution have a

[16]It is assumed 4 times a year inspections & routine maintenance are performed
[17]Argued from the weight factors assigned to the saws in the cutting steps

significant effect on the economic result of technology-based dismantling.

The ecological delta obtained equalled 8 $\$/LDT$ to 2,350 $\$/LDT$, whereas the social eco-costs delta equalled about 2,475 $\$/LDT$. When accounting for the eco-costs in the sustainability profit it came forward that technology-based dismantling is more profitable than labour-based dismantling, from a true price perspective. However, the result of the South Asian competition scenario is negative from a pure economic point of view. Therefore, the true pricing perspective provides a tangible insight in what the monetary bridge is to create an equal level playing field. The substantiation for the ecological analysis follows the structure where first a standard annual process simulation for the four designated commercial segments is performed. This sets the standard for the process input and output, and energy requirements. Secondly, the streams of interest and relevance per phase of the dismantling concept need to be identified from these simulations. Thirdly, the ecological insights and eco-costs need to be coupled to the streams of interest. Lastly, an expression needs to be derived establishing the delta between technology-based and labour-based dismantling. For the social analysis the amount of child labour, work related mortalities and injuries, and extreme poverty has to be quantified. The quantification is argued by means of literature. The economic analysis provides the coupling between the process as described in section 5.3 and the CAPEX and OPEX, where the inclusion of the eco-costs is also discussed.

### 5.4.1. Ecological Impact Analysis

The annual process simulation provides a throughput approximation where the material streams distribution is quantified according to table 5.9. For the ecological analysis, the focus is on the value stream of the main material - steel. It has been decided to express the ecological impact of a technology-based dismantling concept as the threshold, where the added $CO_2$ and ecological costs for the conventional scenarios are surplus. This way an insight is provided in the theoretical added costs of the conventional production chain of steel. The throughput resulting from the technology-based dismantling simulation is adhered to as the quantity to be processed in all scenarios. The scope for the ecological impact analysis comprises of the input, including potential vessel demobilisation from the designated area, the dismantling process, and the steel production process. As elaborated on in section 3.7, the threshold consists of no demobilisation, dismantling through a technology-based concept, where the steel acts as feedstock for a local EAF steel production facility. The three plausible scenarios are repeated for convenience:

1. Demobilisation to South Asia. Here, the vessel is dismantled through a beaching process, where the gained steel acts as feedstock for a BOF steel production process [i.e. melting].
2. Demobilisation to Izmir, Turkey. Here, the vessel is dismantled through a landing process, where the gained steel acts as feedstock for an EAF steel production process - [*Turkey 1*].
3. No demobilisation, but dismantled through a technology-based dismantling concept in North West Europe. After dismantling the steel is transported by ship to Turkey, where it acts as feedstock for an EAF steel production process - [*Turkey 2*].

For the demobilisation the approximated bunker quantity as discussed in section 5.1.3 is used. This allows for the calculation of the $CO_2$ equivalent and ecological eco-costs. Note that the eco-costs as displayed in this section are not equal to the demobilisation costs as shown in table 5.7, due to the true pricing nature of the eco-costs method.

Similar to the OPEX costs for conventional dismantling as shown in table 2.2 in section 2.1.2, the eco-costs of the conventional dismantling phase consist mainly of the usage of LPG/oxygen cutting. In (Deshpande et al., 2013) it is argued that the amount of LPG and oxygen required for dismantling a vessel can be expressed in terms of $kg/km \cdot mm$. It is stated that for a 10,000 LDT vessel, an equivalent of 52,000 kg $CO_2$ is emitted. Furthermore, standard normal distributed equations for the amount of LPG and oxygen per $kg/km \cdot mm$ are provided. From the stoichiometric values for LPG, it could be determined how many cuts and LPG and oxygen are needed for the dismantling of such a 10,000 LDT vessel as described. From this the required amount of LPG and oxygen in $kg/LDT$ can be approximated. From the required quantity of LPG and oxygen in $kg/LDT$, the aggregated amount for the throughput derived from the simulation can be calculated. From this the $CO_2$ and eco-costs can be derived by means of ("Eco Costs Value", 2023). Furthermore, the amount of non-economic waste of the designated vessel selection is known through table 5.9. The material element *Joinery* is an economic stream and thus sold in South Asia, while *minerals*, *plastics*, *liquids, chemicals & gasses*, and *miscellaneous* [i.e. paint] end up either on a landfill, get dumped in sea, or is emitted in the air and sediment during cutting (Rahman et al., 2016), (Deshpande et al., 2013). Moreover, it has been assumed that in Turkey the cutting process is identical to South Asia's cutting process, but waste management is performed carefully. This assumption is made based on the inclusion of several yards in the *EU Green Recycling Yards* list for EU SRR compliant dismantling. This results in no landfill or sea dumping of waste streams, but burned paint is emitted only into the air. The decision-making of no paint ending up in the sediment, just as in South Asia, rest on the landing methodology where concrete flooring is used.

For the steel production process a distinction has been made between BOF and EAF production processes. For the North West Europe and Turkey scenario EAF is the selected production process. The decision-making rests on the fact that most of Turkish production capacity originates from EAF mills, and the steel production in West Turkey is purely EAF ("STATISTICS", n.d.). In the EU there are numerous production locations using this technology [figure 5.8], and recently incentives from the EU have aided in realising a larger near future EAF production capacity[18]. Most importantly in relation to this research, EAF is a much cleaner production method in terms of GHG emissions. The eco-costs 2023 overview of ("Eco Costs Value", 2023) does not include a cost for BOF steel production in South Asia. As a substitution the substance *Steel (21% sec = standard mix average) EU hot rolled coil* has been taken to provide insight in the South Asian steel production eco-costs. Furthermore, EAF steel production is not included in the overview at all. Therefore, a percentage of the values for EU hot rolled coil have been taken, based on the $CO_2$ emissions of EAF compared to BOF. For the determination of this percentage, the required amount of steel scrap as feedstock for each production process has been taken into account, to ensure accuracy for the amount of non-emitted $CO_2$ of EAF compared to BOF. This percentage equals 2.3% [equation 5.4], where the input is derived from ("What is the carbon footprint of steel?", 2023) and the percentage of secondary steel [i.e. scrap steel] as listed in the eco-costs overview.

$$EAF_{\%} = 1 - \frac{EAF_{CO_2 \text{ saved}/t}}{BOF_{CO_2/t}} = 1 - \left(\frac{\frac{1.987-0.357}{105\%-21.0\%}}{1.987}\right) = 2.34\% \tag{5.4}$$

All relevant substances from the eco-costs have been identified from ("Eco Costs Value", 2023) in relation to the company's wastes, emissions and products. The $\Delta P^{ecol}_{LDT}$ part of equation 3.2, as displayed in section 3.5.2 is used for determining the total eco-cost per phase, as an aggregate of all technologies used to minimise the eco-costs. The results of the methodology have been structured that the calculated $\Delta$ equals the difference in eco-costs associated with a technology-based dismantling concept, versus the described scenarios, aligning (Zore et al., 2017). The unburdening effects calculated for wastes are those that are converted into green products within the new process [i.e. waste into energy from the PCU, no usage of landfill]. For new green products produced, the unburdening effects within a selected supply chain phase are those which otherwise would have had environmentally more harmful substitutes in terms of materials, energy, or services [i.e. steel making process decision (BOF or EAF), and transport need to Turkey in the case of scenario 3]. For the technology-based dismantling threshold the burdening effects of the process are the energy usage, and unspent wastes within its own production process [i.e. ash and carbon black of PCU], together with all other burdening effects related to the production of the new products [i.e. the EAF steel making process]. The ecological contribution to the sustainability profit is highlighted in equation 5.5. Table 5.12 provides insight in the used eco-costs substances, and table 5.13 until 5.16 provide an overview of the $\Delta CO_2$ of all scenarios and commercial classes, including the associated total eco-costs. This quantification is also included in the SVSM.

[18]Based on Bloomberg article *Thyssenkrupp Gets EU Approval for €2 Billion Green Steel Aid* published on July 20$^{th}$ 2023

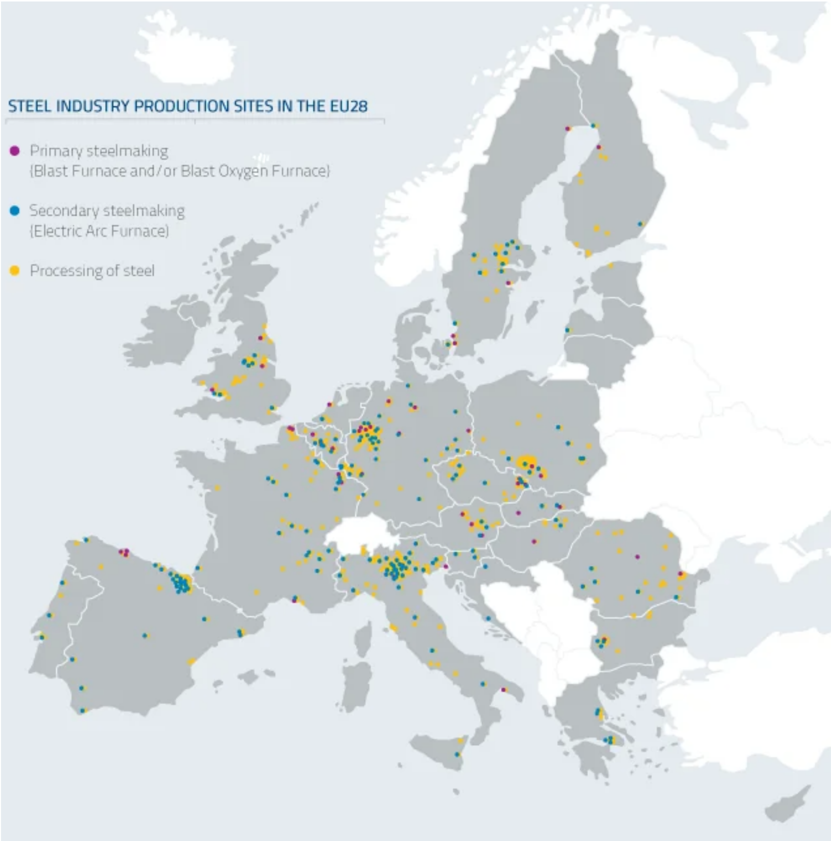



**Figure 5.8:** Steel production locations EU

$$\Delta P^{ecol} = \Big( \sum_{t \epsilon T} \sum_{i \epsilon R_T^{UNB}} \Delta q_{m_i}^{R_{UNB,consumed}} \cdot c_{i,t}^{R_{UNB}} + \sum_{t \epsilon T} \sum_{i \epsilon R_T^{UNB}} \Delta q_{m_j}^{P_{UNB,consumed}} \cdot f_j^{S/P_{UNB}} \cdot c_{j,t}^{S} \Big) - \Big( \sum_{t \epsilon T} \sum_{i \epsilon R_T^{B}} \Delta ( q_{m_i}^{R_{B,tot}} - q_{m_i}^{R_{UNB,consumed}} \cdot c_{i,t}^{R_B} ) + \sum_{t \epsilon T} \sum_{i \epsilon R_T^{B}} \Delta q_{m_j}^{P_B} \cdot c_{j,t}^{P_B} \Big) - \tag{5.5}$$

**Table 5.12:** Eco-cost substances

| Substance | Quantity | Unit |
|---|---|---|
| Electricity Industrial use Netherlands (EI data, obsolete)[19] | 0.0085511 | $/kWh |
| Bulk carrier Handysize dwt 16.383, 12.5 knots | 0.0015853 | $/t km |
| Diesel low-sulphur including combustion $CO_2$ | 1.0115213 | $/kg |
| Steel (21% sec = standard mix average) EU hot rolled coil | 0.2129393 | $/kg |
| Steel EAF | 0.0049858 | $/kg |
| LPG including combustion $CO_2$ | 913.41959 | $/kg |
| MAP Oxygen gas at 1 bar 0 ° C | 0.1224885 | $/kg |

[19]Circumscribed from $/MJ to $/kWh

**Table 5.13:** Ecological delta eco-costs results - container ships

| Phase | North West EU | Δ South Asia | Δ Turkey 1 | Δ Turkey 2 | Unit |
|---|---|---|---|---|---|
| Demobilisation | 0.00 | 0.367 | 0.175 | 0.000 | $CO_2$/LDT |
| Dismantling | 0.0767 | 4.400 | 4.400 | 0.000 | $CO_2$/LDT |
| Production & Transport | 0.357 | 1.940 | 0.000 | 0.148 | $CO_2$/LDT |
| Total | 0.434 | 6.708 | 4.575 | 0.148 | $CO_2$/LDT |
| Demobilisation | 0.00 | 119.26 | 56.75 | 0.00 | $/LDT |
| Dismantling | 0.11 | 1,361.97 | 1,351.70 | 0.00 | $/LDT |
| Production & Transport | 30.30 | 866.51 | 0.00 | 9.41 | $/LDT |
| Total | 30.41 | 2,375.83 | 1,408.45 | 9.41 | $/LDT |

**Table 5.14:** Ecological delta eco-costs results - product tankers

| Phase | North West EU | Δ South Asia | Δ Turkey 1 | Δ Turkey 2 | Unit |
|---|---|---|---|---|---|
| Demobilisation | 0.00 | 0.413 | 0.196 | 0.000 | $CO_2$/LDT |
| Dismantling | 0.0789 | 4.398 | 4.398 | 0.000 | $CO_2$/LDT |
| Production & Transport | 0.357 | 1.940 | 0.000 | 0.146 | $CO_2$/LDT |
| Total | 0.436 | 6.751 | 4.595 | 0.146 | $CO_2$/LDT |
| Demobilisation | 0.00 | 134.13 | 63.82 | 0.00 | $/LDT |
| Dismantling | 0.11 | 1,374.64 | 1,353.44 | 0.00 | $/LDT |
| Production & Transport | 30.30 | 813.04 | 0.00 | 8.83 | $/LDT |
| Total | 30.41 | 2,348.17 | 1,417.26 | 8.83 | $/LDT |

**Table 5.15:** Ecological delta eco-costs results - MPP vessels

| Phase | North West EU | Δ South Asia | Δ Turkey 1 | Δ Turkey 2 | Unit |
|---|---|---|---|---|---|
| Demobilisation | 0.00 | 0.363 | 0.172 | 0.000 | $CO_2$/LDT |
| Dismantling | 0.0780 | 4.399 | 4.399 | 0.000 | $CO_2$/LDT |
| Production & Transport | 0.357 | 1.940 | 0.000 | 0.146 | $CO_2$/LDT |
| Total | 0.435 | 6.702 | 4.571 | 0.146 | $CO_2$/LDT |
| Demobilisation | 0.00 | 117.79 | 55.85 | 0.00 | $/LDT |
| Dismantling | 0.11 | 1,365.49 | 1,353.18 | 0.00 | $/LDT |
| Production & Transport | 30.30 | 849.41 | 0.00 | 9.23 | $/LDT |
| Total | 30.41 | 2,360.22 | 1,409.03 | 9.23 | $/LDT |

**Table 5.16:** Ecological delta eco-costs results - GC vessels

| Phase | North West EU | Δ South Asia | Δ Turkey 1 | Δ Turkey 2 | Unit |
|---|---|---|---|---|---|
| Demobilisation | 0.00 | 0.320 | 0.152 | 0.000 | $CO_2$/LDT |
| Dismantling | 0.0972 | 4.380 | 4.380 | 0.000 | $CO_2$/LDT |
| Production & Transport | 0.357 | 1.940 | 0.000 | 0.145 | $CO_2$/LDT |
| Total | 0.454 | 6.640 | 4.532 | 0.145 | $CO_2$/LDT |
| Demobilisation | 0.00 | 103.91 | 49.39 | 0.00 | $/LDT |
| Dismantling | 0.11 | 1,373.32 | 1,353.33 | 0.00 | $/LDT |
| Production & Transport | 30.30 | 847.93 | 0.00 | 9.21 | $/LDT |
| Total | 30.41 | 2,352.65 | 1,402.72 | 9.21 | $/LDT |

The tables above provide from left to right an overview of the phase related ecological eco-costs. Here, the North West EU column represents the threshold scenario. The three columns to the right are the additional eco-costs of the three scenarios, compared to the threshold. As can be observed, the impact in terms eco-costs is minimal between the different vessel types. In practice occurrences happen such as oil spillage triggered by externalities [argued from the process]. Elements such as human mistakes during cleaning and cutting are difficult to quantify in an generalised year simulation. This could explain the minimal difference between the vessel types, despite potential oil spillage of a tanker being larger than of a GC vessel.

### 5.4.2. Social Impact Analysis

For the determination of the social-economic costs associated with current practices in South Asia and Turkey the applicable eco-costs social compartments have been used. By means of literature an approximation of the annual dismantling capacity per site, the number of workers, and the percentage of child labour has been established. The Turkish [privately owned] dismantling yard consists of 29 plots of land with a demolishing capacity of up to 600,000 tonnes per annum. This provides employments for about 800–1200 people at full capacity (Neşer et al., 2008), averaging out at 1000 contracted people. Through literature and online media research no signs have been found of child labour in the Turkish shipbreaking industry.

For the South Asia approximation, use has been made of several sources to determine the relevant parameters. In 2019 a research was published substantiating the conditions, and quantities of child labour in Bangladesh located yards. For labour to be eligible as child labour, the threshold is 14 years old, or the end of compulsory schooling[20] for non-hazardous work. However, due to the dangerous nature of shipbreaking, for both ILO law and standards as well as local Bangladeshi law, the threshold is 18 years. Despite these age conditions for working in the shipbreaking industry (Chowdhury, 2020) found that during day shifts 8% of all workers are under this threshold, and during the night shifts 20% of all workers are under this threshold. This averages out at 13% of all workers under the legal age, and thus considered child labour. According to ("Research Mission on the situation of Shipbreaking workers in South Asia", 2013), based on yard visits in Gadani, Pakistan, the dismantling capacity equals 1,000,000 LDT per year spread over 130 land plots. An average of 15,000 people are contracted on these plots.

The equation used to obtain the social eco-costs is visible in 5.6, and the overview of all social eco-costs and used parameters is visible in tables 5.17 and 5.18. From the calculated social eco-costs can be derived that the influence of the social costs expressed per handled ton of vessel is very significant, and the differences between the scoped regions are large. Therefore, the social eco-costs will be included separately in the sustainable value stream maps, which will be covered in section 5.5.

$$\Delta SC_{LDT} = \sum_{t \epsilon T} \Delta N_t^{jobs} \cdot c_s^{Comp} \tag{5.6}$$

**Table 5.17:** Parameters

| Parameter | Quantity | Unit |
|---|---|---|
| Yard capacity [annual] | 1,000,000 | LDT |
| Average workers | 15,000 | people |
| Child labour | 13 | % |
| Hours/LDT | 0.006 | hr |
| Operational time/day | 16 | hr |
| Operational time/year | 5840 | hr |
| Yard capacity [annual] | 600,000 | LDT |
| Average workers | 1,000 | people |
| Child labour | 0 | % |
| Hours/LDT | 0.0073 | hr |
| Operational time/day | 12 | hr |
| Operational time/year | 4380 | hr |

**Table 5.18:** Social eco-costs results

| Substance | North West EU | South Asia | Turkey | Unit |
|---|---|---|---|---|
| Child labour, 8 hours/day, 2240 hours yearly | 0 | 406.32 | 0 | $/LDT |
| Work related mortality and injuries [21] | 0 | 114.46 | 7.01 | $/LDT |
| Extreme poverty, wage 0.35$/hr | 0 | 1,955.23 | 0 | $/LDT |
| Total | 0 | 2,476.02 | 7.01 | $/LDT |

### 5.4.3. Economic Analysis

As visible in equation 3.2 in section 3.5.2, the economic delta contribution to the sustainability profit consists of the conventional economic contribution establishing the result of a company. Equation 5.7 highlights the economic contribution to the sustainability profit. Here, $\Delta R_t$ represents the revenue, $\Delta R_t^{sub}$ represents government subsidy, $\Delta E_t$ refers to the annual expenses of the company [OPEX], $\Delta E_t^{ecotax}$ represents the eco tax $\Delta I_t$ represents the annual required investments, and $\Delta D_t$ represents the annual depreciation [see table 3.4 for further declaration on the parameters of the sustainability profit].

$$\Delta P^{econ} = \Delta R_t + \Delta R_t^{sub} - \Delta E_t - \Delta E_t^{ecotax} - \Delta I_t - \Delta D_t^{econ} \tag{5.7}$$

[20]whichever is higher

First all investments and operational expenses related to process phases are linked to the appropriate parameter. It is proposed that the annual acquisition costs for the vessels are placed under investments, and not operational expenses. For the acquisition costs per commercial segment, the equations as presented in table 5.6 have been used, after which the demobilisation advantage determined in section 5.1.3 is subtracted. Besides the acquisition costs, the investment parameter consists of the annual amortisation of the financing required to develop the concept. The assumptions made for this are an investment horizon of 15 years, 3% interest rate[22], and a linear amortisation structure. The required investments for technology-based dismantling have been categorised according to the same classification as the energy demand profile discussed in section 5.3.2. Some machinery rests on proven technology, but the configuration required for technology-based dismantling is new and unique. Therefore, not for all process-related investments adequate literature substantiation could be found to approximate the costs price. Moreover, the value of equipment, and therefor the required investment, is very time-dependent. Therefore, it was deemed sufficiently accurate for this study to make substantiated estimations on asset price in case no relatable material exists.

Further assumptions made regarding the assets are the following. The valuation of the lifting pontoon is based on a known newbuild price for a 210 $m$ submersible pontoon, where in this case a second hand price is approximated and checked with expert knowledge. The price also includes a refit from diesel driven pumps to electrically driven pumps. The asset price for the saws have been estimated, since no similar technology [with the requirements of cutting through ship grade steel] currently exists [23]. The costs for the stripping units is based on heavy duty robotics from the automotive industry ("What Is the Real Cost of an Industrial Robot Arm?", 2017). The costs for the hydro blasting units is based on asset prices of industrial hydro blasting units, with a surplus since the reference hydro blasting units require manual handling. The laser cutting units assets price is approximated in a similar manner to the hydro blasting units ("How much does a laser cutting machine cost?", 2022). The loading and haulage systems are based on autonomous haulage systems from the mining industry due to the similar loading requirements[24] ("Distraction or disruption? Autonomous trucks gain ground in US logistics", 2018). For the totality of the system integration of the automated block processing unit a factor of 50% is maintained. For all pumping units the same pump price and quantity is taken, based on industrial pumps. The price is calculated based on the expected energy demand and the approximations for the cost of ownership distribution provided by ("Pump systems and total cost of ownership", n.d.). For the water treatment an additional investment and system integration margin is taken based on ("How much does an industrial water treatment system cost?", 2023). For the pyrolysis unit a total system cost have been drawn from (Yun, 2012), where the required amount of feedstock is the determining factor. The commercial segment with the largest possible PCU feedstock, and a safety margin of 10%, have been taken to determine the price. All other process steps have an assumed investment need of $0, except various other systems which is set at $1,000,000 for the inclusion of a certain level of calculated financial redundancy, and loose equipment. The reason all other process requirements have an investment of $0 is that they are infrastructure related. It is presumed that the technology-based dismantling concept will be implemented on an existing yard, implying that these requirements are already present.

Moreover, the assumption has been made that the amount of eco tax allocated to the scope 2 emissions of the machinery [Energy Tax], the process water replenishment quantity [Tax on mains water] are granted as an incentive by the local government ("Environmental taxes. Taxation and Businesses", 2016). This implies the assumption that $\Delta R_t^{sub}$ and $\Delta E_t^{ecotax}$ cancel each other out. The revenues generated by the technology-based dismantling concept are based on the scrap prices of certain materials such as steel, copper, bronze, and electronic scrap. The most important price determination is the price of steel. As stated in section 5.2, the price per ton steel was determined based on the annual average of 2022 of the German scrap steel market[25]. For this E3 grade steel has been used ("Metal Price Monitor 2022 - RETRALOG®", n.d.). The same methodologies has been used for copper and bronze, where monthly fluctuations in the FOREX have been taken into account in circumscription to $US.

[22]Generous green financing terms are adhered to due to the nature of the investment

[23]The only relatable technology is from the *Kursk* salvage operation performed by Mammoet-Smit. However, only the total salvage contract value is public information. No indications of saw costs are published

[24]Average cost price truck plus the automation kit

[25]The reason for this is that the German scrap steel market is more stable on monthly basis than the Dutch scrap steel market. The Dutch scrap steel market knows daily fluctuations

Lastly, the annual asset depreciation. The annual depreciation has been set to zero in the same timeline as the financing horizon, where a salvage value of 10% is maintained at economical end-of-life. The result, on an annual basis for the OPEX, is visible in figure 5.9. Here, the weighted average of all 4 commercial class simulations is taken to provide a more clear insight. In reality, there are some deviations. Especially surrounding the PCU unit [around step 20]. The markings represent the process related costs [first mark], the supporting facilities related costs [second mark], and finally the service related costs [third mark].

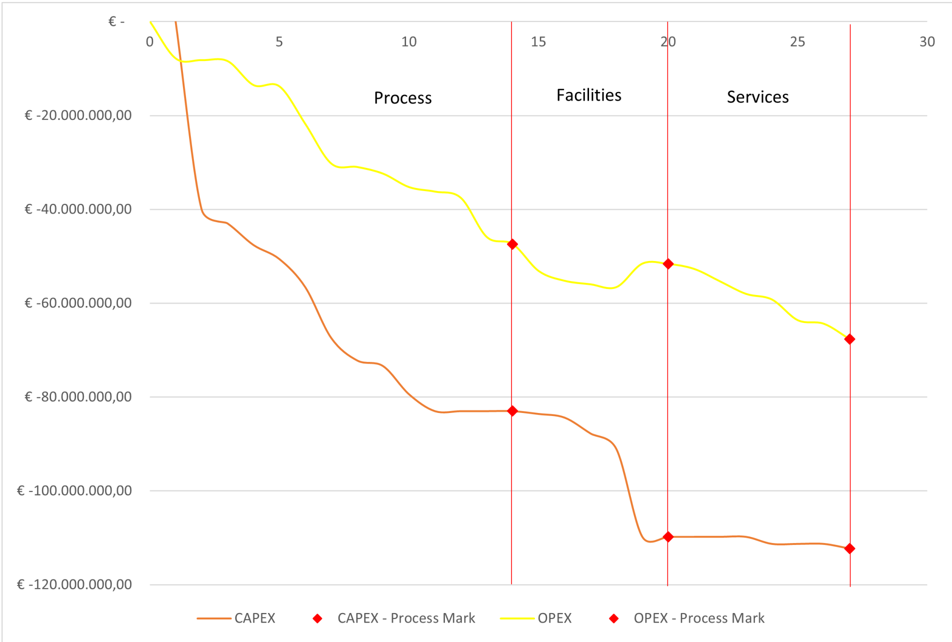



**Figure 5.9:** Cost estimations of CAPEX and annual OPEX

### 5.4.4. Results, Discussion and Conclusion

The overall conclusion from the results is that it is noticeable that the true pricing of the ecological and social impact has a substantial contribution to the pricing of a ton of steel. Furthermore, it is notable that driving competition, purely on economical grounds, on the acquisition of vessels based on the pricing maintained in South Asia is not feasible, even when a demobilisation discount is included in the price. However, this does not necessarily mean that the competitive position is unfortunate. When including the delta generated by the ecological and social costs of the beaching methodology and BOF steel production method, the level of competitiveness compared to South India is remarkably good. The reason for stating it strongly is because the actual steel price at the moment is about $525[26], implying a 9 to 9.5 better price in terms of sustainable profitability. Furthermore, the economic result on competing with South Asia compared to the the true pricing perspective provides a tangible insight in what the monetary bridge is to create an equal level playing field for vessel dismantling.

When looking at the two scenarios in Turkey it becomes clear that the economical contribution of the sustainability profit is more stressing on the overall performance of the dismantling process. The reasons for this are the absence of child labour, and the fact that Turkey has a very strong EAF steel production industry. Despite the ambitions with respect to steel production technology in the European Union, exporting the scrap steel to Turkey is [especially on the short notice] not an unrealistic scenario. When comparing it to local ship dismantling using the landing methodology, the technology-based concept does score much better in terms of the sustainability profit.

[26]Circumscribed from Chines Yen to $US. Source: https://tradingeconomics.com/commodity/steel

**Table 5.19:** Sustainability profit - scenario 1

| | Container | Product Tanker | MPP | GC | Unit |
|---|---|---|---|---|---|
| $\Delta P^{econ}$ | -84.10 | -171.08 | 0.72 | -224.14 | $/LDT |
| $\Delta P^{ecol}$ | 2,375.83 | 2,320.63 | 2,360.22 | 2,352.65 | $/LDT |
| $\Delta P^{soc}$ | 2,476.02 | 2,476.02 | 2,476.02 | 2,476.02 | $/LDT |
| $\Delta SP$ | 4,767.75 | 4,625.57 | 4,836.96 | 4,604.53 | $/LDT |

**Table 5.20:** Sustainability profit - scenario 2

| | Container | Product Tanker | MPP | GC | Unit |
|---|---|---|---|---|---|
| $\Delta P^{econ}$ | 0.00 | 0.00 | 0.00 | 0.00 | $/LDT |
| $\Delta P^{ecol}$ | 1,408.45 | 1,417.26 | 1,409.03 | 1,402.72 | $/LDT |
| $\Delta P^{soc}$ | 7.01 | 7.01 | 7.01 | 7.01 | $/LDT |
| $\Delta SP$ | 1,415.46 | 1,415.46 | 1,416.04 | 1,409.73 | $/LDT |

**Table 5.21:** Sustainability profit - scenario 3

| | Container | Product Tanker | MPP | GC | Unit |
|---|---|---|---|---|---|
| $\Delta P^{econ}$ | 34.61 | -47.94 | 19.99 | -45.06 | $/LDT |
| $\Delta P^{ecol}$ | 9.41 | 8.83 | 9.23 | 9.21 | $/LDT |
| $\Delta P^{soc}$ | 0.00 | 0.00 | 0.00 | 0.00 | $/LDT |
| $\Delta SP$ | 44.02 | -39.11 | 29.22 | -35.85 | $/LDT |

## 5.5. Process Mapping

The work of (Brown et al., 2014) has been taken as an exemplary format for designing the SVSM. All parameters discussed in the previous sections are included, providing a comprehensive overview of this research. The results are visible in Appendix C.

## 5.6. Sensitivity Studies

Sensitivity studies have been performed on operations, market workings and externalities, and business model varieties. This allows for the understanding of the effect of potential deviations of business elements on the described scenarios. Through investigating the effect of certain adjustments in operation, more realistic outcome prognosis are established for the concept of technology-based vessel dismantling. The operational adjustment made is a variable operational day of 8 or 16 hours. The results indicate that continuous, 24 hours a day operation is essential for the economic viability of technology-based dismantling. The market and economic adjustments consist of determining the effect of adjustments in vessel and steel pricing. By investigating price adjustments in both the input [purchase] as well as the output [selling] streams, the most influential negotiation position for economic viability can be identified. From the results can be concluded that price negotiations with the steel offtakers guarantee a much larger influence on the business case outcome. Besides price adjustments the influence of the presence of excess oily residue in the cargo tanks of tankers has been investigated. The results show that residual oil has a minimal business impact due to the large gap before being fully self supplying in terms of energy. This implies that residual oil is a "nice to have", but not something to be centralised in the proposition of technology-based dismantling. The business model adjustments concern the absence of the pyrolysis unit and securing marine components for the re-manufacturing market. Ruling out the pyrolysis unit saves initial investment, but increases the annual operational costs. In the case where the waste streams serve as feedstock for the offtakers, and adequate waste management can be secured implying no additional eco-costs, excluding the pyrolysis unit could be an economic consideration. Operating as a supplier for the re-manufacturing market is not considered achievable. The underlying reason for this is the crucialness of time for technology-based dismantling, resulting in a required markup from the extracted machinery for re-manufacturing which is considered not achievable.

[26] An average is taken of the characterisation factor of Bangladesh, India & Pakistan for South Asia

### 5.6.1. Operational Adjustments

The operational adjustments will consist of adjusting the operational time per day. In the standard case the operational profile is set at 24 hours a day, with an annual downtime of 3% to account for preventative maintenance and saw exchanges. The reason why a 24 hour operation is deemed achievable is due to the fact that the yard is located in a port, where in the case of North West Europe an abundance of [petro]chemical companies are housed. Since these plants run continuously, it is deemed achievable under environmental code to also operate 24 hours a day. However, it is yet uncertain what level of noise will be generated by a technology-based dismantling facility. Therefore, keeping in mind that the noise levels could exceed the noise standards for 24 hours operation, it is important to determine a prognosis on the effect of shorter operational days.

In terms of operation there are two differences. Firstly, the operational window is shorter per year, thus a smaller throughput will be achieved. Secondly, as explained in section 5.3.2, the systems and machinery used for the vessel dismantling require a startup energy quantity. If the operation is shut down on a daily basis, the amount of energy required rises relatively, which suggests that the annual operational expenses should also rise relatively. Two scenarios will be investigated; an operational day of 8 hours, and an operational day of 16 hours. Only scenario 1 & 3 are of importance for determining the impact on the $\Delta$ economic eco-costs, since in scenario 2 no technology-based dismantling takes place. All other parameters are kept equal. The result is visible in table 5.22.

**Table 5.22:** Economic eco-cost effect - operational day adjustment

| | Container | Product Tanker | MPP | GC | Unit |
|---|---|---|---|---|---|
| $\Delta P^{econ}_{1,8hr}$ | -186.47 | -284.13 | -98.53 | -356.27 | \$/LDT |
| $\Delta P^{econ}_{3,8hr}$ | -67.77 | -160.99 | -79.26 | -177.19 | \$/LDT |
| $\Delta P^{econ}_{1,16hr}$ | -109.10 | -198.94 | -25.65 | -256.80 | \$/LDT |
| $\Delta P^{econ}_{3,16hr}$ | 9.61 | -75.8 | -6.38 | -77.73 | \$/LDT |

As can be concluded by the economic eco-costs above, having an as large as lawfully possible operational day has an enormous impact on the economic performance of a technology-based dismantling yard. When comparing the outcome with the standard situation [24 hours operation] as portrayed in tables 5.19 until 5.21 it becomes visible that especially for driving competition with Turkey [which is deemed the most real scenario due to the vessel sizes and the geographic location selected for this research] the operational daily up time is a huge precondition for economic viability.

### 5.6.2. Market and Economic Adjustments

The market & economic adjustments will consists of manipulating the steel price [i.e. investigate the operational results for a monetary value award towards green vessel dismantling], and the impact of potential residual oil in the tanks of product tankers. The reason that the vessel/steel price adjustments has been selected as a relevant scenario is because of its relation to economic viability of technology-based dismantling. Moreover, creating understanding of what part of the ecological and social true price must be accounted for in the economic valuation per LDT is considered valuable information in the ambition towards environmentally sounds dismantling. This makes the required willingness of shipowners, or governmental incentive programs, tangible. The impact of residual oil in the cargo tanks is deemed important due to the overall emphasise on energy usage throughout this report. As stated in section 5.3.2, used energy only has an indirect added value to the output products and is pure cash out. Obtaining insight in potential scenarios minimising energy purchase is therefore justified.

#### Price Manipulation

It could be argued from the delta in eco-costs as provided by tables 5.19 until 5.21 that the economic prognosis should be higher due to the delta realised by the ecological & social eco-costs. Currently, shipowners and steel manufacturers are focused primarily on the economic value of EoL vessels and the steel originating from this, despite global criticism. This sensitivity study will provide insight in the effect of shipowners' willingness in receiving a lower valuation on their vessel, and steel owners receiving a higher quote on their feedstock steel scrap. The two case studies will be performed separately to see which of the two influences the economic result of technology-based scrapping more.

The approach followed is a bottom up approach. Through this methodology the decrease/increase for acquisition costs and selling price is determined, respectively. The argument for cost adjustments is already justified by the true pricing through eco-costs of the current practices, but this study would provide insight in what part of the ecological and social eco-costs need to be mitigated to the economic eco-costs to break even. The first case study is the required decrease in acquisition price per segment. Since the economical eco-costs are determined per LDT, the required price decrement for the commercial classes to reach BEP equals the economic eco-costs. The relevant scenarios for this case study are scenario 1 & 3. Table 5.23 provides an overview of the custom acquisition price[27], the BEP acquisition price, the percentile difference between the custom acquisition price and the BEP price, and the percentage expressed as willingness [i.e. the price adjustment Δ as a percentage of the ecological and social eco-costs].

**Table 5.23:** Acquisition cost price adjustment

| | Container | Product Tanker | MPP | GC | Unit |
|---|---|---|---|---|---|
| $\Delta P_1^{econ}$ | -84.10 | -171.08 | 0.72 | -224.14 | $/LDT |
| $\Delta P_3^{econ}$ | 34.61 | -47.94 | 19.99 | -45.06 | $/LDT |
| $BEP_{SA}$ | 232.98 | 230.53 | 238.49 | 177.58 | $/LDT |
| $P_1$ % | 26.5 | 42.6 | -0.30 | 55.8 | % |
| $P_3$ % | -17.5 | 17.2 | -9.15 | 20.2 | % |
| $\%_{will,1}$ | 1.73 | 3.57 | -0.01 | 4.64 | % |
| $\%_{will,3}$ | -367.7 | 542.8 | -216.7 | 489.2 | % |

To determine the scrap steel price increment for achieving an economic eco-costs BEP is less straight forward. The reason for this is that steel is not the only product sold from vessel dismantling. Therefore, the BEP steel price is determined in an iterative manner. Table 5.24 provides an overview of the required steel price and the markup percentage.

**Table 5.24:** Steel price cost price adjustment

| | Container | Product Tanker | MPP | GC | Unit |
|---|---|---|---|---|---|
| $P_{standard}$ | 386.82 | 386.82 | 386.82 | 386.82 | $/LDT |
| $P_{adj,1}$ | 475.78 | 576.07 | 386.05 | 634.14 | $/LDT |
| $P_{adj,3}$ | 350.21 | 439.85 | 365.53 | 436.54 | $/LDT |
| $\Delta_{\%,1}$ | 23.0 | 48.9 | -0.20 | 63.94 | % |
| $\Delta_{\%,3}$ | -9.46 | 13.7 | -5.50 | 12.9 | % |

The note on the approach followed for establishing the required steel price and acquisition price, is that the effects are modelled separately. In reality, the parameters are not independent of each other, and interact. They are both macro-economic parameters involved in the ship dismantling supply and demand market. However, steel price negotiations seem to have a larger impact on the viability of the business model at a smaller percentile adjustments.

### Oily Residue

Commonly, tanker owners clean and ventilate their cargo holds after every contract, except for tankers that solely carry one specific type of load [line contract]. This is due to demands of insurance bodies that set standards (Association, 2020), and for the prevention of contamination, which is demanded by contractors. Contamination could lead to useless feedstock/product resulting in economic damage. However, it can be agreed upon to not clean the tank and sludge tank before the arrival at the technology-based dismantling yard. This would save time, and thus money related to crew, insurance, etc., for the owner. Moreover, the residual oil left in the cargo holds is a beneficiary addition to the PCU feedstock stream. Therefore, a factorial addition in the mass percentage of the weight category associated with residual oils and lubes in tanks is investigated.

[27] With custom is meant including the demobilisation advantage

The factor chosen is a increment of 50% for *liquids, chemicals & gasses* with respect to the standard case. Due to the commercial segments included in this study only consisting of one tanker type, this is the only relevant commercial class for this sensitivity study. The relevant changes occur in the power-to-need %, and the effect of this on the operational expenses. Table 5.25 shows the changes in the ratio and OPEX for the product tanker, on an annual basis.

**Table 5.25:** Sensitivity study - Residual Oil

| | Power-to-need% | OPEX [$] | Power-to-need% | OPEX [$] |
|---|---|---|---|---|
| **Product Tanker** | 22.49 | 65,824,265.44 | 25.41 | 64,813,853.98 |

The result is an annual savings of about $1,000,000 and a self-sufficiency increment of about 3%. The result of this change in costs for the product tanker segment is the difference between a $\Delta P^{econ}$ of -$171.08/LDT [standard case], and a $\Delta P^{econ}$ of -$168.16/LDT for scenario 1. For scenario 3 the difference is $\Delta P^{econ}$ of -$47.94/LDT [standard case], and a $\Delta P^{econ}$ of -$45.02/LDT [scenario 3]. This small difference can have a significant influence over the investment horizon, but the predictability of the quantity of oily residues during acquisition of the tankers is difficult. The exception, and possible solution, for this is demanding "dirty" tanks and including this in the pricing strategy. However, this results presumably in a higher acquisition price, which could negatively leverage the gains in OPEX in the CAPEX. The result on annual CAPEX and OPEX is visible in figure 5.10.

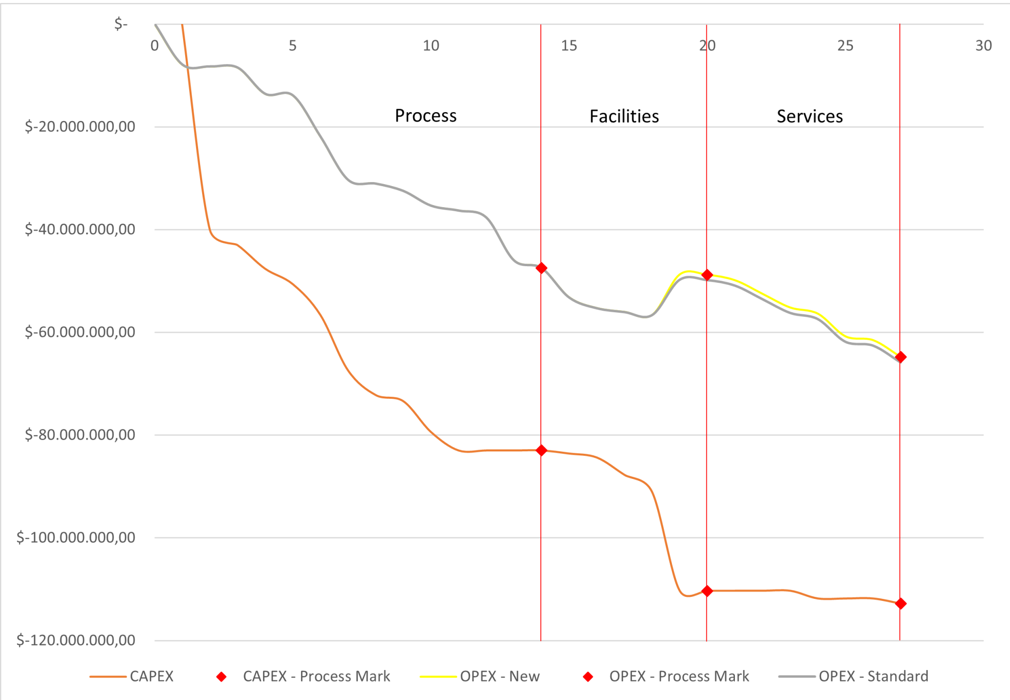



**Figure 5.10:** Cost estimations of CAPEX and annual OPEX - Oily residue sensitivity study

### 5.6.3. Business Model Adjustments

The sensitivity study related to business model adjustments covers the exclusion of the pyrolysis unit from the technology-based dismantling facility, and includes the role of supplier for the re-manufacturing of marine components. The reason for investigating the exclusion of the pyrolysis unit is the large investment required, especially when including the financing costs. However, partial self sufficiency of energy could provide such a discount in the operational expenses that this investment is justified. In order to substantiate this the exclusion of the PCU unit will be compared to including the PCU unit. Re-manufacturing is not the core business for a technology-based dismantling facility. Nevertheless, adequate waste management and circularity are deemed of important pillars for such dismantling concept. The upcycling of marine components by means of re-manufacturing could provide additional circular revenue. However, time is key for technology-based dismantling. Therefore, the tipping point in terms of $\$/LDT$ machinery is investigated for its feasibility.

### Exclusion of a Pyrolysis Unit

To ensure proper waste management, professional companies will retrieve the waste. This decision implies no investment costs related to the PCU, but also no self-reliance in terms of a certain percentage of the required electricity generation. Therefore, it will be investigated what price level is deemed high enough to cover the additional electricity costs, in the case that the PCU is not included. For this sensitivity study it is assumed that the professional waste management companies will not landfill the retrieved waste, but perform a process similar to the pyrolysis unit. This implies no alternations to the ecological eco-costs of the technology-based dismantling process. Besides the adjustments described above, no further changes have been made in pricing or operational parameters.

The operational expenses on annual basis increase by $3,300,000 to $6,900,000, depending on the commercial class. This equals the amount of electricity costs saved by having a pyrolysis unit, minus the electricity demand of the PCU and the accessory machinery. The commercial types with a larger mass percentage of indirect economic value [i.e. *Joinery*, *minerals*, *plastics*, *liquids*, *chemicals & gasses*, and *miscellaneous*] would generate more electricity, and thus a minimisation of the OPEX. However, an investment of almost $19,000,000, which results in a total CAPEX cost of ownership of almost $30,000,000 [including financing costs], is saved by means of the elimination of the pyrolysis unit and accessory machinery. Simulated over an entire year, the company's overall economic performance increases much due to the large decrement in required financing, including compounded interest, despite the additional OPEX. Furthermore, if the waste collection [assuming it will act as a feedstock to the offtaker] generates $250 - $320, the original operational expenses prognosis is reached. Considering the monetary benefits of the electricity potential of the economic waste streams, this pricing is deemed achievable in the case of thermal gasification units or incineration. The key figures are displayed in table 5.26. The CAPEX and annual OPEX for this sensitivity study are visible in figure 5.11, and the resulting sustainable profit per commercial class are visible in table 5.27 until 5.29.

**Table 5.26:** Sensitivity study - elimination of PCU

| | Container | Product Tanker | MPP | GC | Unit |
|---|---|---|---|---|---|
| $\Delta OPEX$ | 3,364,675 | 6,884,423 | 3,883,876 | 6,778,528 | $ |
| Waste Stream [wet & dry] | 13,252 | 23,699 | 15,382 | 18,792 | t |
| Waste Price Target | 253.91 | 290.49 | 252.50 | 313.17 | $ |
| Electricity Potential | 10,645,488 | 19,444,856 | 11,943,490 | 16,946,318 | kWh |
| Electricity Income Potential[28] | 345.10 | 356.99 | 329.73 | 410.63 | $\$/t_{waste}$ |

**Table 5.27:** Sustainability profit - scenario 1 PCU eliminated

| | Container | Product Tanker | MPP | GC | Unit |
|---|---|---|---|---|---|
| $\Delta P^{econ}$ | -63.96 | -136.65 | 23.00 | -186.97 | $/LDT |
| $\Delta P^{ecol}$ | 2,375.64 | 2,320.43 | 2,360.17 | 2,352.60 | $/LDT |
| $\Delta P^{soc}$ | 2,476.02 | 2,476.02 | 2,476.02 | 2,476.02 | $/LDT |
| $\Delta SP$ | 4,787.70 | 4,659.80 | 4,859.20 | 4,641.65 | $/LDT |

**Table 5.28:** Sustainability profit - scenario 2 PCU eliminated

| | Container | Product Tanker | MPP | GC | Unit |
|---|---|---|---|---|---|
| $\Delta P^{econ}$ | 0.00 | 0.00 | 0.00 | 0.00 | $/LDT |
| $\Delta P^{ecol}$ | 1,408.25 | 1,408.25 | 1,408.99 | 1,402.68 | $/LDT |
| $\Delta P^{soc}$ | 7.01 | 7.01 | 7.01 | 7.01 | $/LDT |
| $\Delta SP$ | 1,415.26 | 1,415.26 | 1,416.00 | 1,406.69 | $/LDT |

[28] From the offtaker perspective

**Table 5.29:** Sustainability profit - scenario 3 PCU eliminated

| | Container | Product Tanker | MPP | GC | Unit |
|---|---|---|---|---|---|
| $\Delta P^{econ}$ | 54.75 | -13.51 | 42.27 | -7.89 | \$/LDT |
| $\Delta P^{ecol}$ | 9.41 | 8.83 | 9.23 | 9.21 | \$/LDT |
| $\Delta P^{soc}$ | 0.00 | 0.00 | 0.00 | 0.00 | \$/LDT |
| $\Delta SP$ | 64.16 | -4.67 | 51.50 | 1.32 | \$/LDT |

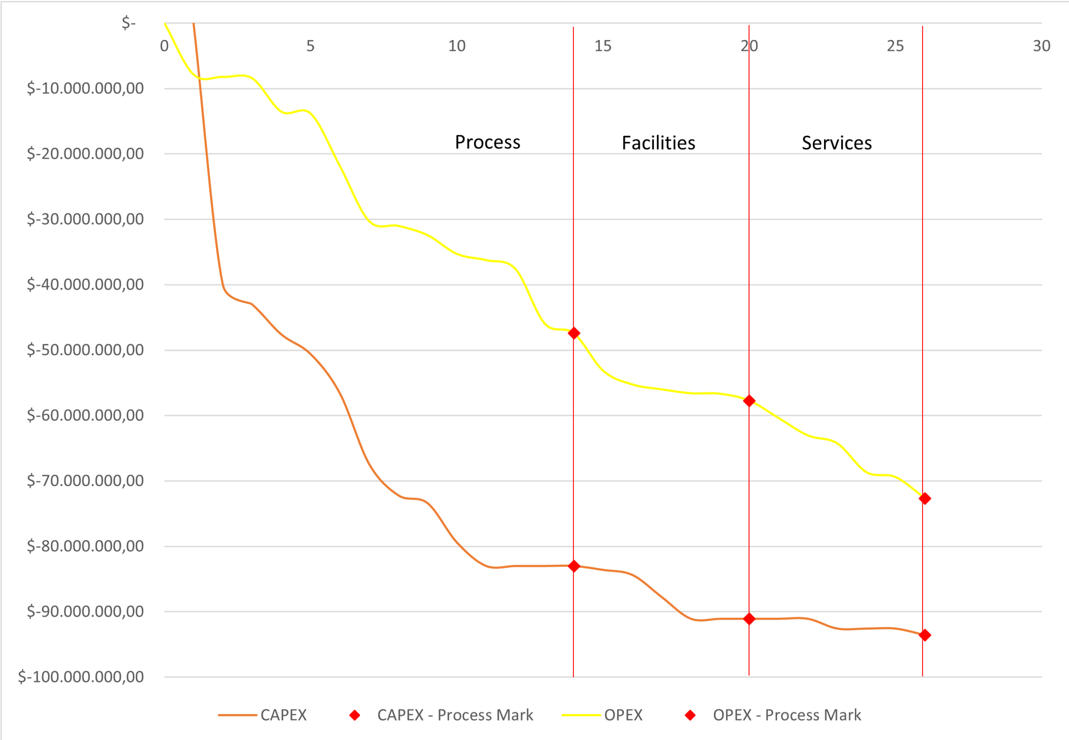



**Figure 5.11:** Cost estimations of CAPEX and annual OPEX - PCU sensitivity study

### Machinery for Re-manufacturing

Taking out the machinery to sell it for re-manufacturing instead of making the machinery nonoperational during the cutting stage is a time-dependent decision. Most machinery dismantling can only occur while on land, thus after the pontoon lifting operation and ship transfer. From that moment on the process is mostly sequential, and the total lead time is considered the biggest parameters for operational viability. In order to determine the potential additional gains from carefully dismantling machinery like the main engine[s], axis, PTO systems, etc. the revenue stream for the weight element *Machinery* must justify the additional losses in time, and therefor annual throughput capacity. To provide insight in the potential of additional re-manufacturing income the minimum price $\Delta/LDT$ for machinery compared to the steel price has been determined. This insight provides insight in the monetary threshold for the tradeoff of modelling the careful dismantling fully to see the effect.

Firstly, the hourly OPEX and CAPEX[29] have been determined in the standard scenario. Secondly, the amount [t] per hour of machinery processed is determined. For this the assumption has been made that machinery is evenly distributed over the ship's length, while in reality machinery is mostly located at the aft. Lastly, the machinery price markup $\Delta/LDT$ in comparison to the steel price is determined. From this can be concluded, under standard operations, what costs must be justified per LDT machinery. Table 5.30 provides an overview of the outcomes.

[29] Taken at the financing quantity and horizon

**Table 5.30:** Key numbers re-manufacturing calculation

| | Container | Product Tanker | MPP | GC | Unit |
|---|---|---|---|---|---|
| OPEX | 8,130.61 | 7,747.68 | 8,088.97 | 7,887.86 | $/hr |
| CAPEX | 1,372.57 | 1,372.57 | 1,372.57 | 1,372.57 | $/hr |
| $LDT_{mach}$ | 2.522 | 2.680 | 2.908 | 1.212 | LDT/hr |
| $\Delta P^{econ}$ | 3,381.75 | 3,016.25 | 2,866.76 | 7,254.91 | $/LDT |

It is clear that smaller vessels in terms of LDT must have significant amounts of machinery aboard to not become an outlier in cost justification [GC vessel is small with relatively little machinery, the product tanker is also smaller, but has a relative high amount of machinery aboard]. The cost markup of about $3,000/LDT average for the other three commercial segments seems too large for further investigation. The reason for this is that besides that this price markup is large, adjustments to the simulation decreasing the annual throughput due to the required time for careful dismantling, and increase required crew [most likely maritime experienced, thus more expensive crew] would drive up the costs even further. The expectation is that these cost drivers will increase the costs/hour, and that keeping the revenue steady by means of income generated from the items to be re-manufactured will not be achieved. The only condition for dismantlement of the machinery for re-manufacturing is in the case that the dismantling is possible while afloat, during the engineering and preparation phase.

# 6

# Discussion and Recommendations

This section discusses the overall interpretation of the results and the limitations of the study. In this research, assumptions are made to offer a better reflection of reality than leaving elements out of the covered analyses. Assumptions do affect the reliability of the results. Therefore, a disquisition on key assumptions and the potential influence on the outcomes reliability will be proposed. Moreover, recommendations on the scope of the study and the model will be included in this section.

## 6.1. Discussion

First, the interpretation on assumptions will be discussed. A large part of the data is provided by experts such as OEMs, but some parameters are assumed and based on literary argumentation. Explicitly discussing these assumptions and their potential influence increases this study's reliability.

### 6.1.1. Assumptions on Technological Readiness

From the process analysis as discussed in section 5.3 is concluded that the total turnaround time of each vessel block is the key aspect for economic success of technology-based vessel dismantling. Although the values for each time step are considered reliable, because they are derived from the OEMs through *CMT*, it are still calculated/theoretical values. Since technology-based dismantling is currently still a conceptual process, this data is the best possible quality input for the simulation that could be obtained. Besides the data used for modelling, there are also some knowledge gaps on the actual technologies adhered to in the case study. The cutting process by means of saws is presumed achievable under conditions substantiated in section 5.3, but there is no relatable commercially scaled technology that could be used as reference. The most relatable technology is the salvage of the *Kursk* 23 years ago, where the sawing process took a significant time compared to the intended cutting time of the case study. Also, the accessory cooling capacity and saw wear is purely theoretical. Similar conclusions can be drawn from the technological assumptions for the laser cutting technique.

### 6.1.2. Assumptions on Data

As stated multiple times throughout the report, the end of life vessel management is a non-transparent industry. The data, and data set enlargement techniques, used in section 5.1.3 will provide some deviation to reality. Moreover, as discussed and shown in figure A.5, the end of life vessel valuation is very dependent on market externalities such as transport demand and commodity prices. For this research it was deemed accurate enough to adhere to the valuation - size relation as proposed. However, in reality including the variation over time, in a forecasted matter based on historical trends, in the valuation would improve the quality of the data. Also, the data set for the market dynamics research for the vessel selection covers the time span of the Covid-19 era. Although it is substantiated that no real disruptions in terms of commercial class are expected due to the transshipment role of these ports, this era does influence the reliability of the data set to a certain level.

Secondly, the data concerning the eco-costs tool derived from ("Eco Costs Value", 2023). The ecological eco-costs established in section 5.4.1 provide a relevant insight on the true pricing impact of conventional dismantling processes, compared to technology-based dismantling processes. However, the data set does not provide eco-costs values for the steel manufacturing techniques, in the designated geographical area. Insight was gained by means of setting out parallels in terms of geographic area, and the relation in $CO_2$ impact between the two manufacturing techniques. For the purpose of this research this suffices, but it would be interesting to reevaluate the results if/when ("Eco Costs Value", 2023) includes the correct manufacturing technique and geographic area. Similar statements can be made on the social eco-costs. The quantification of child labour, occupational hazards and poverty are based on literature research. The statistics presented in the studies from 2020 are taken as a measurement for current practices. However, improvements could be possible.

## 6.2. Recommendations

This section includes recommendations regarding follow-up research in the field of technology-based dismantling concepts.

### 6.2.1. Inclusion of a Emission Trading System

The market dynamics section argues that the acquisition of a locally present fleet allows for a demobilisation advantage during vessel purchases. This way the technology-based dismantling concept connects their feedstock to local supply. In the near future carbon tax for vessel owners with a gross tonnage larger than 5,000 tonnes will be implemented. When aiming to acquire vessels that exceed the 5,000 GT threshold [potentially this threshold drops in the future as well], including the costs associated with this carbon tax legislative framework will likely strengthen the position of technology-based dismantling yards. Besides the inclusion of maritime traffic in the EU emission trading system, the effect of diminishing freely allocated carbon credits to among others steel manufacturers will most likely also alter the supply and demand of scrap steel.

### 6.2.2. Technical Feasibility

As already stated in the section above covering the assumptions on technological readiness, the turnaround times of some crucial technological solutions have been obtained by means of *CMT*. However, some questions on the technical feasibility of some of the techniques proposed have been deliberated in section 5.3. The main question is how the cutting technique will cope with vibrations, both its own as well as the induced vibrations by the structure. A possible solution for dealing with vibrations is suggested as well, but more accurate modelling of this effect could strengthen, or rule out, this technology selection. Moreover, opting for a broader technology solution list and comparing the operational and technological difference could be a complementary research on the tool made for this research.

### 6.2.3. Contractual Study

The legislative framework on waste management as discussed in section 2.2.2 requires a significant amount of paperwork on vessel import [flag state related], Inventory of Hazardous Material, insurances, and intercommunication to local enforcing authorities. Considering the required volume, in terms of LDT and vessels, for technology-based dismantling to justify investment and operational costs, a standard framework for document management could be helpful. To guarantee compliance with all relevant regulations, such a study implies a legal basis for the argumentation of the validity of the framework.

# 7 Conclusion

As described in the introduction in chapter 1, the goal of this research was to investigate and substantiate the level of competitiveness of technology-based vessel dismantling concepts located in North West Europe. The need for adjusting the vessels dismantling industry's way of working was highlighted in chapter 2, where the adverse impact to the environment and occupational hazards were discussed. Also, the historical development of the dismantling industry has been analysed, including the effect of legislation on changing the industry's working. More sustainable practices and measuring parameters for these concepts are highlighted in section 2.3, whereas the introduction of the actual case study was discussed in chapter 4. Through the identification of current knowledge gaps in academic research, potential methodologies were examined in chapter 3. The scope includes selecting an appropriate fleet segment for the designated region, and measurement and visualisation tools for substantiating the operational-economic differences between technology-based dismantling and labour-based dismantling, whilst including the added value and costs of technology for coping with the adverse impacts of the conventional industry. The methodologies selected were needed to construct support for answering the main question:

**What is the level of competitiveness of technology-based, environmentally sound vessel dismantling located in North Western Europe?**

In order to substantiate the answer of the main question, several subjects of interest must be investigated. The sub-questions relevant for this research question were:

1. What are the drivers and workings of the dismantling industry, and what are the adverse consequences of conventional practices?
2. What is the most suitable fleet segment for vessel dismantling in the designated region, and how are these segments valued at End of Life?
3. What material streams constitute the selected fleet segments?
4. What are the key operational-economic parameters for technology-based dismantling?
5. What is the ecological, social and economic impact of technology-based dismantling?
6. How does technology-based vessel dismantling compare to the conventional practices from a single unit perspective?
7. What is the effect of potential operational and market deviations on the economic viability of technology-based vessel dismantling?

The results of the apprehended methodologies in this research allow for comparable scenarios between conventional practices and technology-based dismantling. On the ground of the findings it can be concluded that on pure economic terms, technology-based dismantling is viable for competing with the practices maintained in Turkey. This conclusion stands on the assumption that in both scenarios the Turkish historical valuation - size relation is used. The scenario where dismantling happens in North West Europe and the scrap steel is transported to Turkey as feedstock for EAF steel production also provides a selection of commercial fleet segments resulting in a viable outcome. However, when maintaining the South Asian valuation - size relation, the results indicate that technology-based dismantling barely breaks even in the MPP segment, and makes significant losses per processed LDT for all other commercial segments. This leads one to believe that, from a purely economic standpoint, adhering the pricing level of South Asia is currently not achievable, set by the operational constraints of the scope of this research.

However, when including the ecological and social delta, derived from comparing the threshold true costs of technology-based dismantling to the scenarios described in section 3.7, it becomes clear that the monetised non-economic contribution of technology-based dismantling is large. The sustainable value stream map method was used to provide an overview on the added ecological and social value and operational relevance of the phases within the maintained scope in this research. The outcome of the calculations performed for the visualisation attached in Annex C, show that a lot of the operationally required phases and supporting technologies, have little to no direct added value to the outbound products. However, without supporting facilities like waste separation of the wet streams, the goal of adequate waste management is not achieved. Therefore, it can be deduced that despite the lack of direct added value to the outbound products, the systems are indispensable. The inclusion of self sufficiency of energy on the other hand has proven to be potentially unnecessary. The required investments could be omitted in the case a party is found that purchases selected material streams as feedstock. The financial conditions are a key aspect in this decision-making.

After obtaining and unifying all results for the economic, ecological and social impact in a monetised manner, it was decided to investigate what part of the scenario's ecological and social eco-costs has to be allocated into the economic result [i.e. revenue due to direct relation between revenue and result]. It came forward that about 1% - 5% of the true price of the ecological and social delta has to accounted for in the economic price to break even. This single unit number provides a tangible insight in what the monetary bridge is to create an equal level playing field between technology-based, sustainable vessel dismantling, and the current practices. Moreover, the same BEP price establishment was performed for the outbound products. From the iterative approach followed could be concluded that effectuating agreements on steel prices including an ecological surplus is much more effective than vessel price negotiations. These insights form the basis on how policy makers could create incentives or taxation systems coping with the negative externalities of conventional scrapping, similar to the carbon tax system. From this an equal level playing field arises, incentivising ship owners for sustainable end of life vessel management with the same means that once caused the industry's movement to developing countries.

To conclude, there are both opportunities and challenges for expanding the dismantling capacity in North West Europe by means of implementing technology-based dismantling concepts. From an operational perspective, the minimisation of the turnaround time for every vessel processed is key in spreading the intensive investments over enough earnings, creating economic viability. When looking at the possible competition, adhering to the right pricing level for vessel acquisition and steel sales is key. Especially in the current phase with the absence of incentives and taxation frameworks promoting sustainable vessel dismantling.

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# A

# Market Dynamics

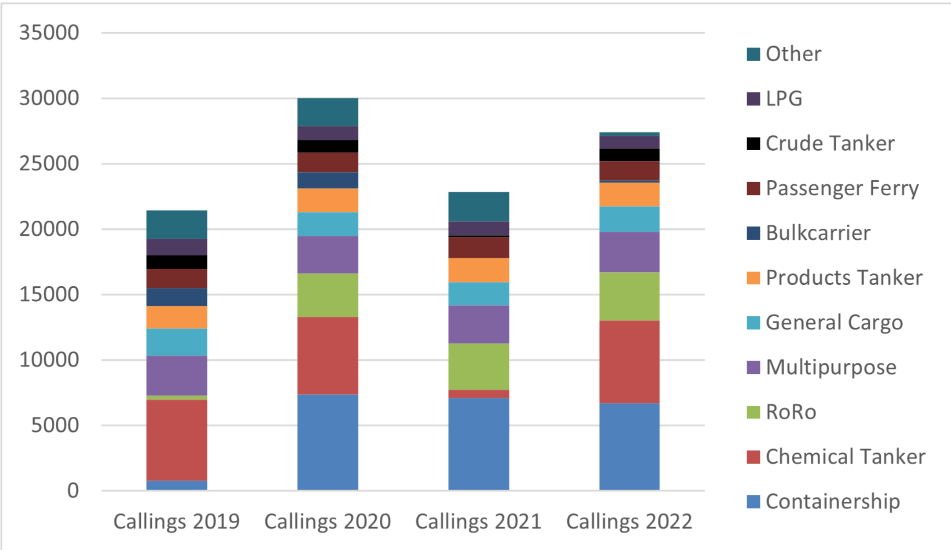


**Figure A.1:** Port callings Port of Rotterdam

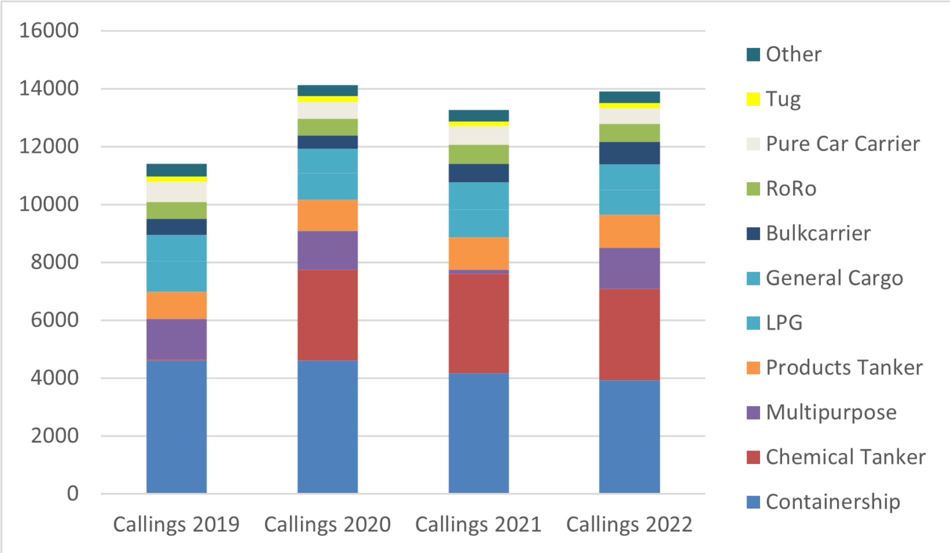


**Figure A.2:** Port callings Port of Antwerp

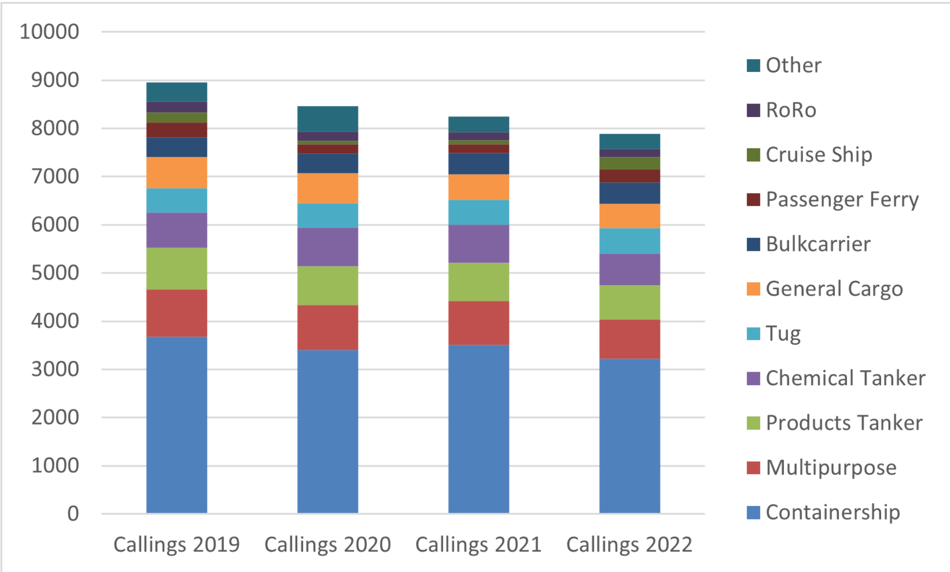


**Figure A.3:** Port callings Port of Hamburg

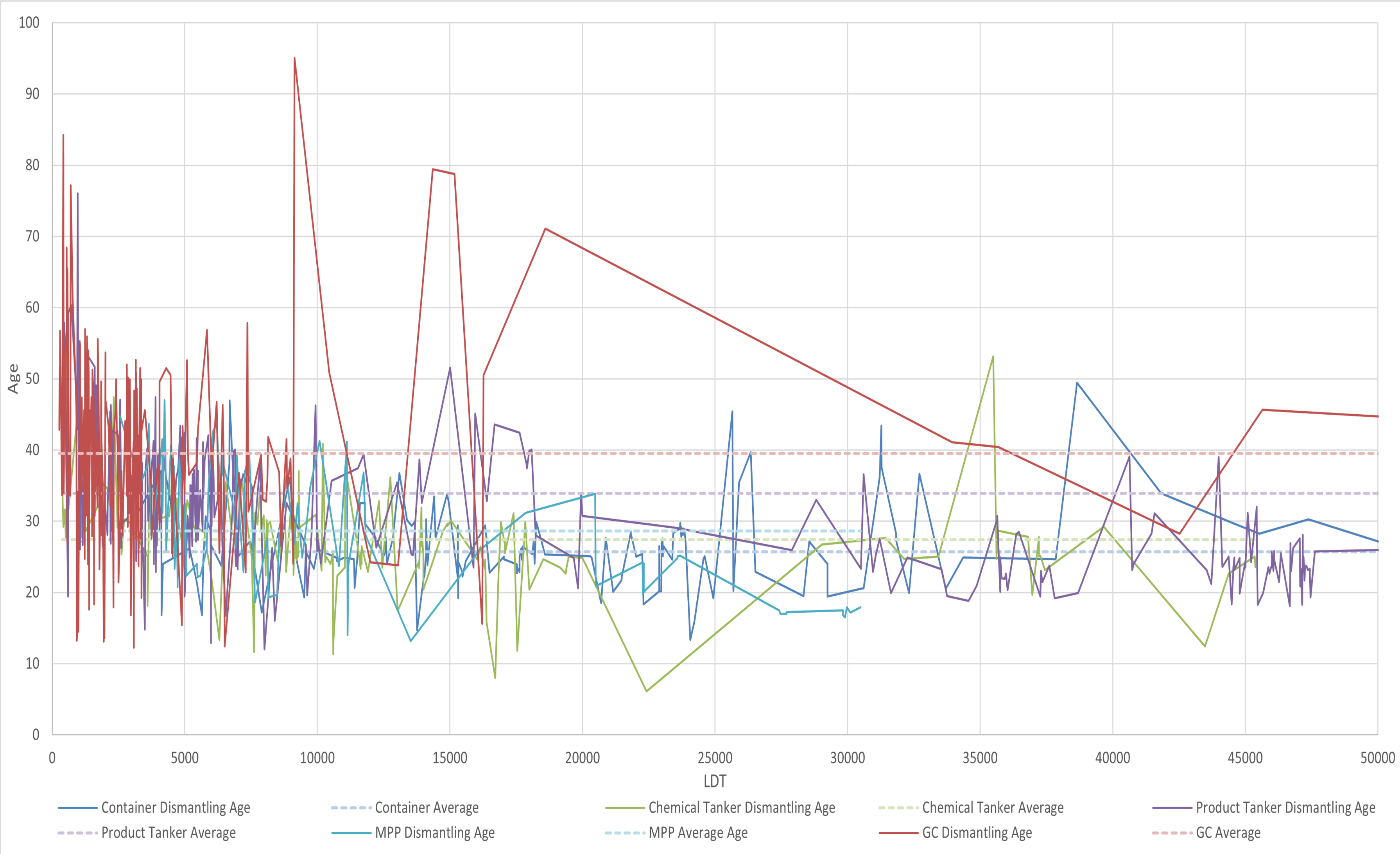


**Figure A.4:** Dismantling Age plotted against DWT

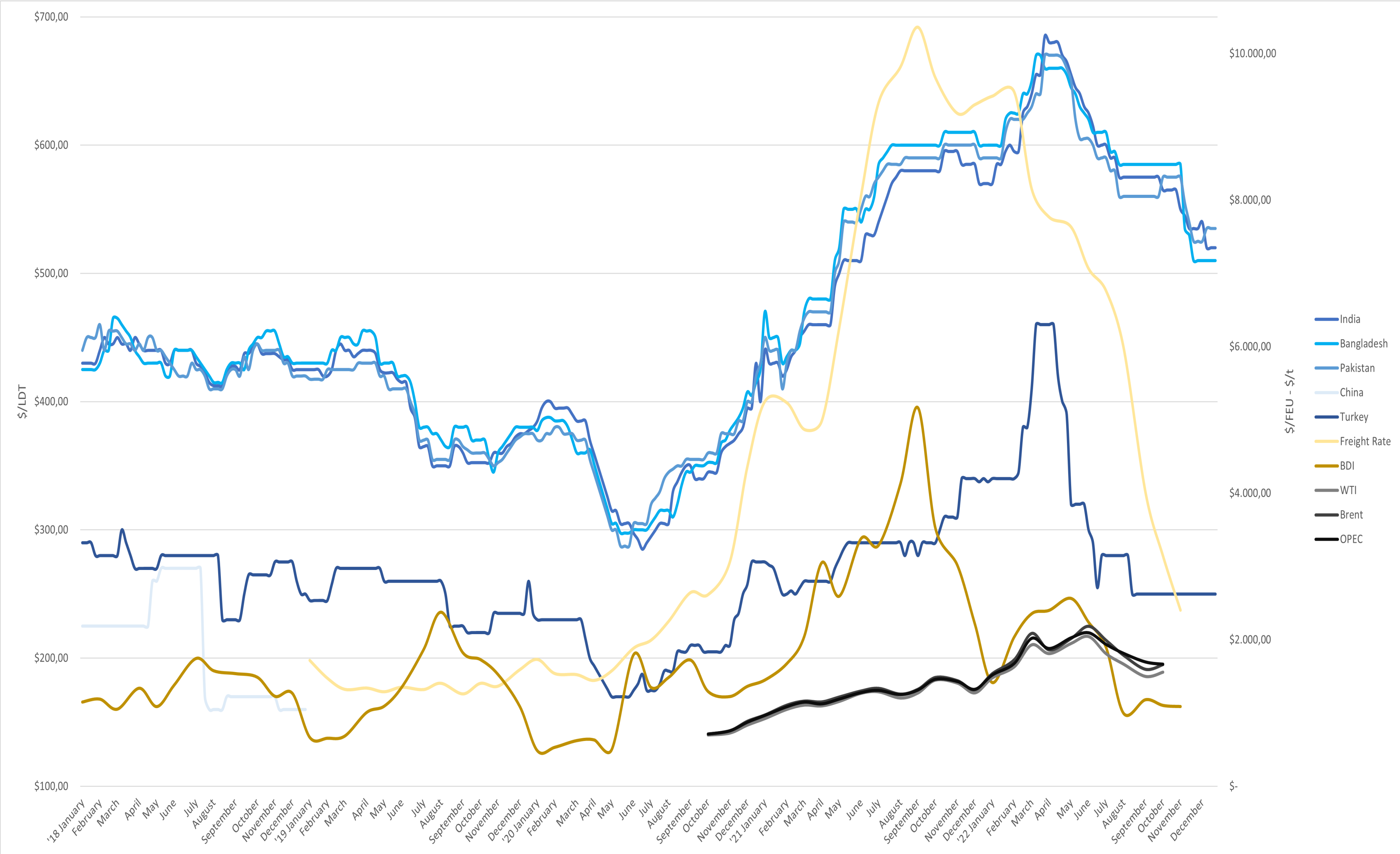


**Figure A.5:** EoL vessel valuation $\$/LDT$ per region, including main commodity price drivers

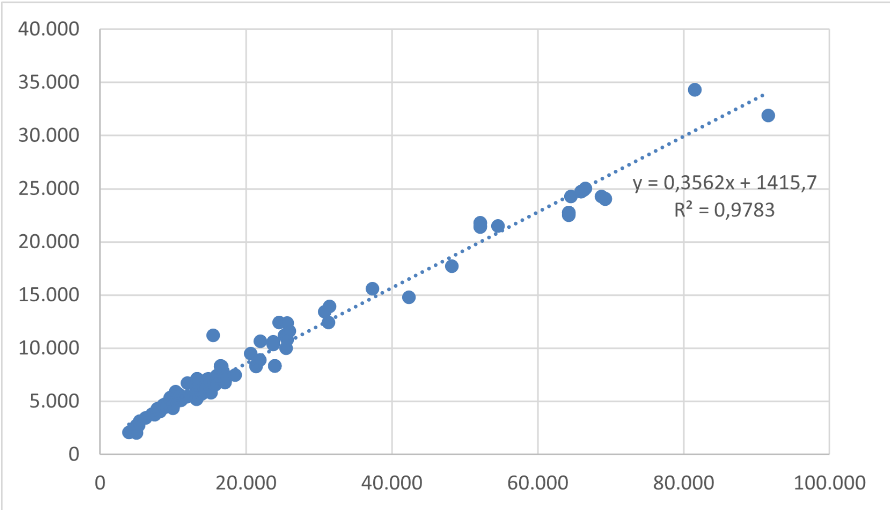


**Figure A.6:** GT-LDT relation container ships

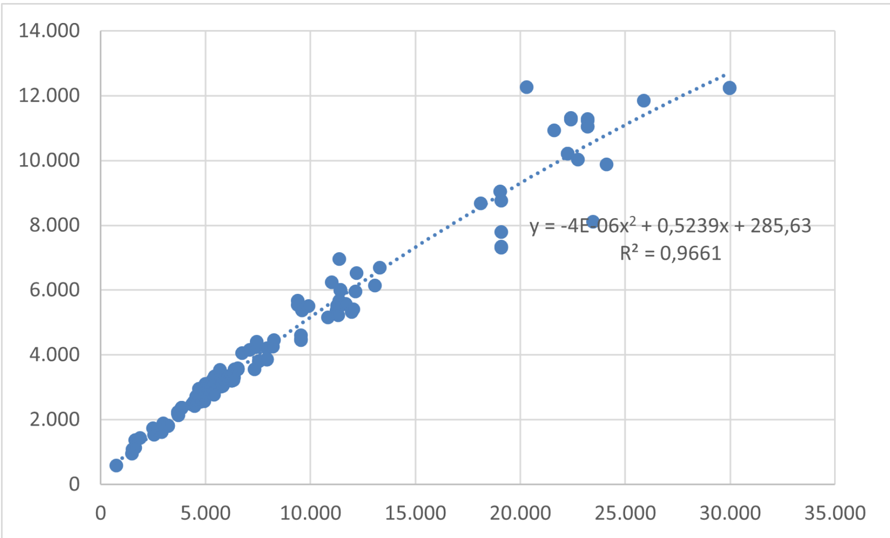


**Figure A.7:** GT-LDT relation chemical tankers

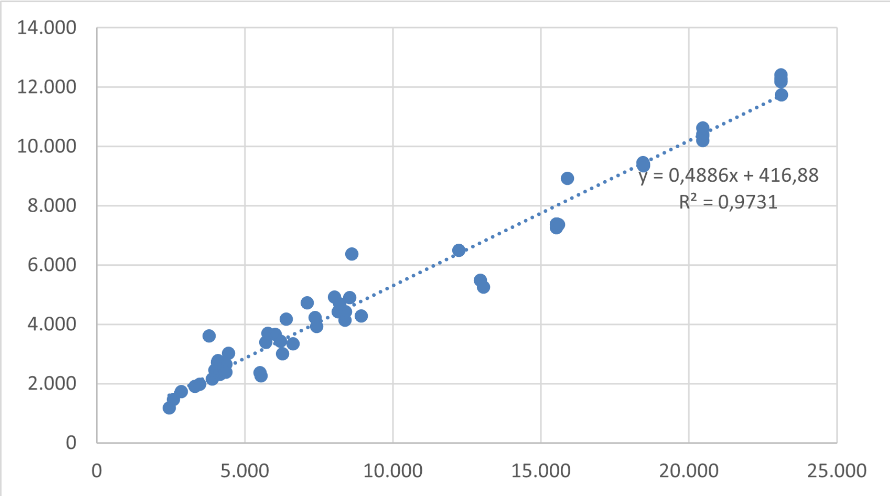


**Figure A.8:** GT-LDT relation MPP vessels

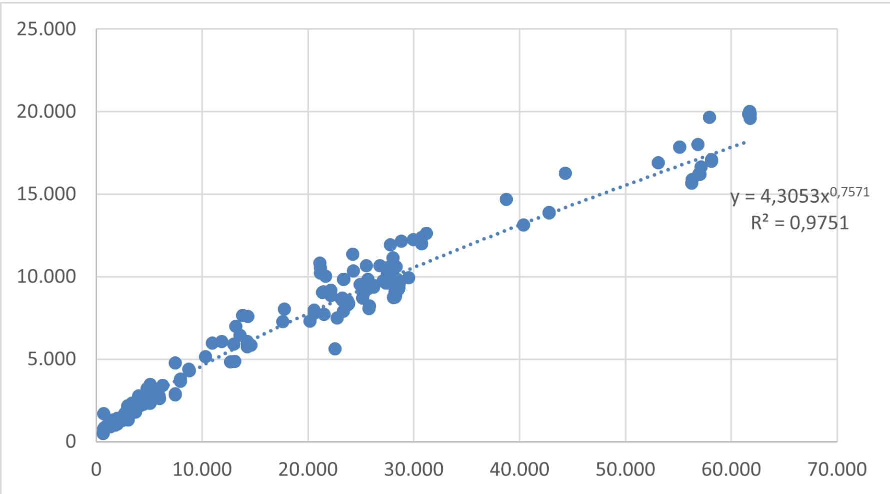


**Figure A.9:** GT-LDT relation product tankers

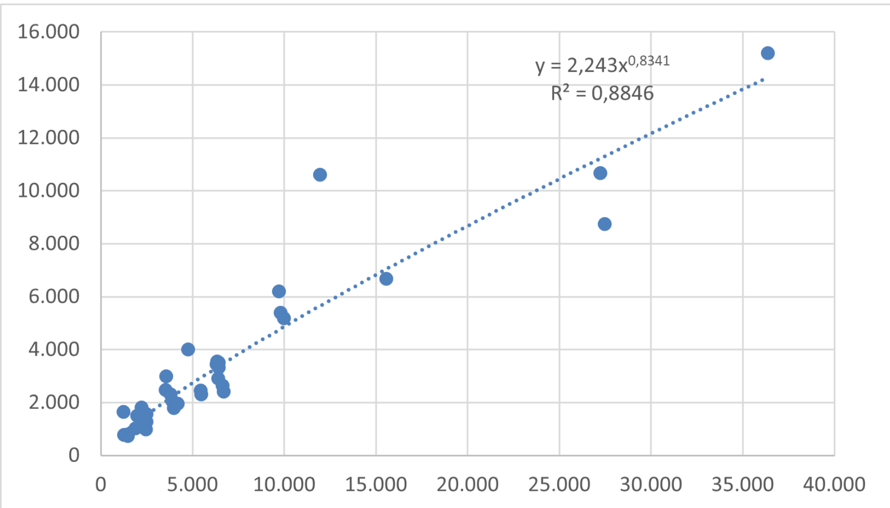


**Figure A.10:** GT-LDT relation GC vessels

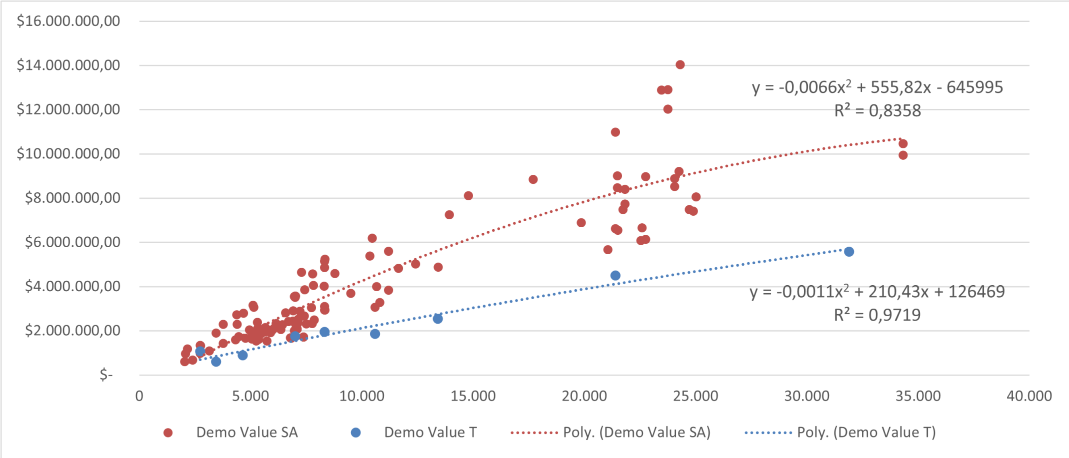


**Figure A.11:** Valuation LDT relation container ships

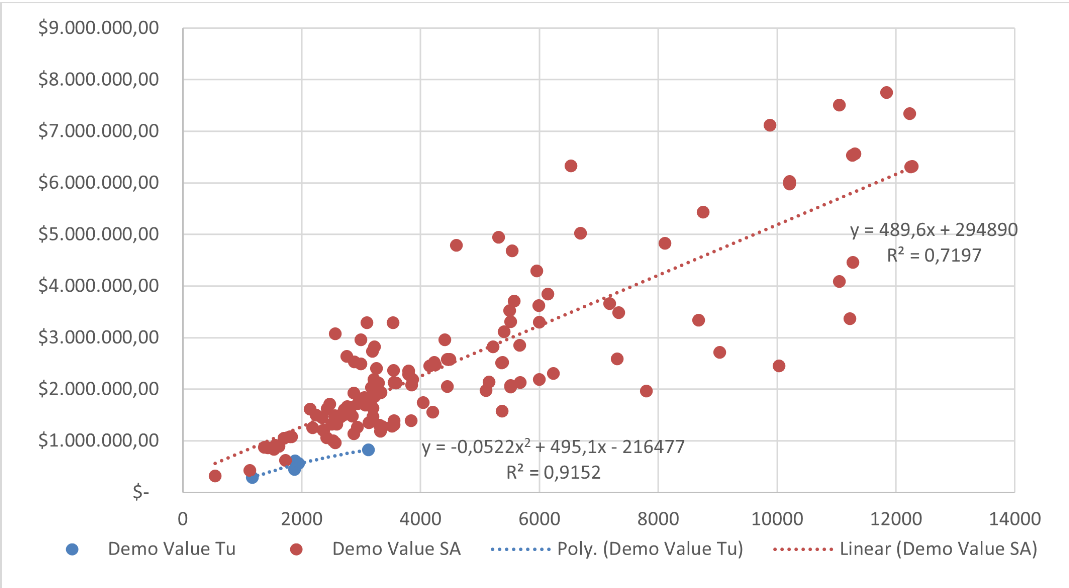


**Figure A.12:** Valuation LDT relation chemical tankers

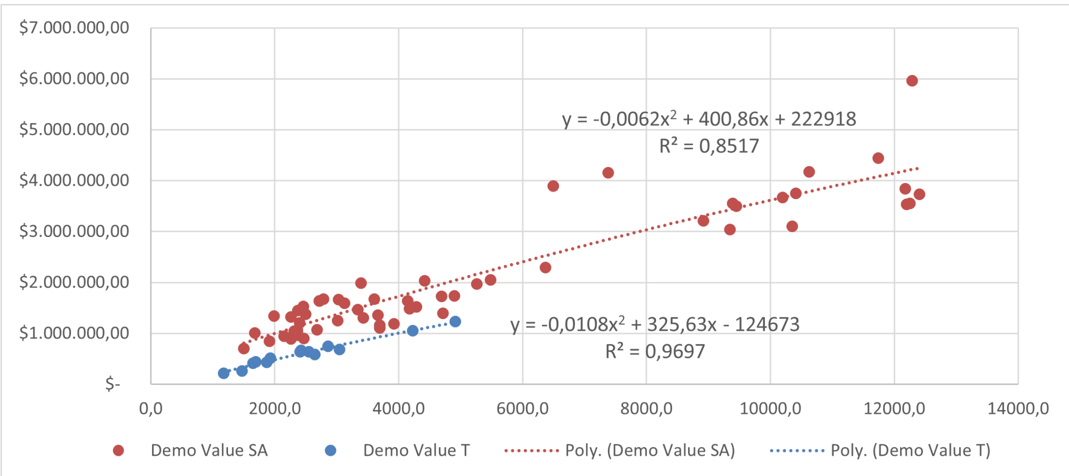


**Figure A.13:** Valuation LDT relation MPP vessels

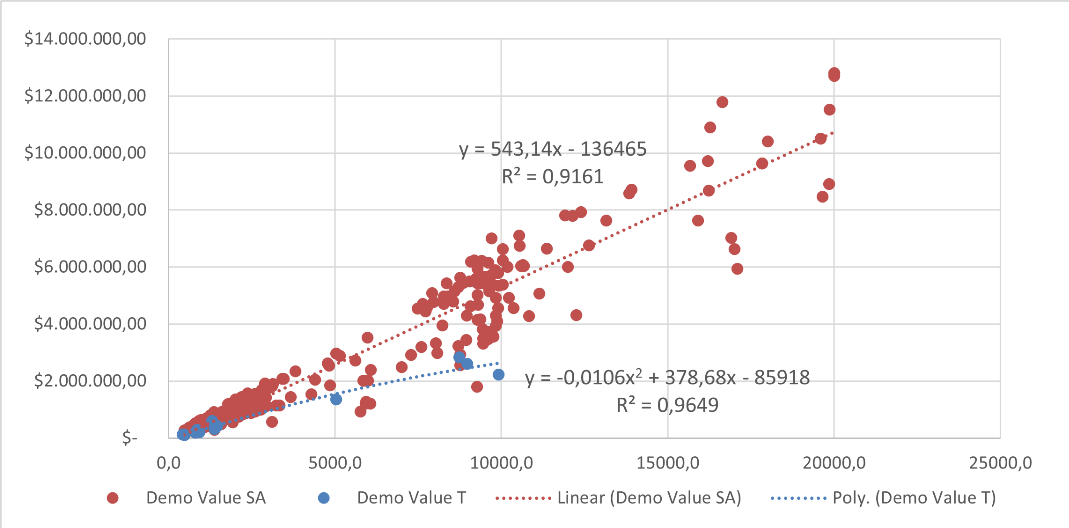


**Figure A.14:** Valuation LDT relation product tankers

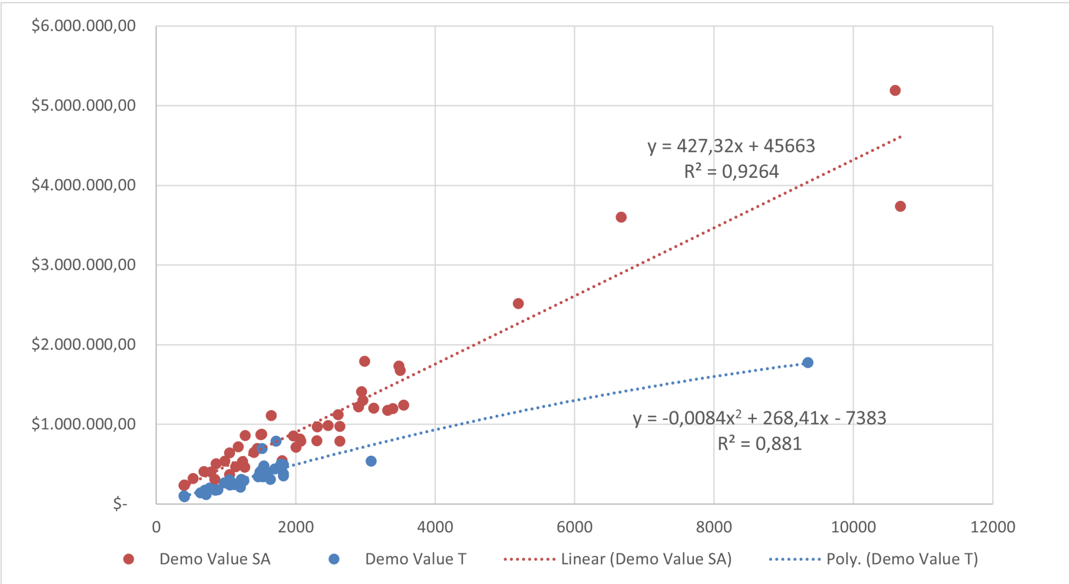


**Figure A.15:** Valuation LDT relation GC vessels

# B

# Material Quantification

**Table B.1:** Transformation matrix #1

| Group | Item | Ferrous | Non-ferrous | Machinery | Electrical & electronic equip. | Minerals | Plastics | Liquids, chemicals & gasses | Joinery | Miscellaneous |
|---|---|---|---|---|---|---|---|---|---|---|
| Machinery piping | Piping [general] | 95% | 5% | | | | | | | |
| Machinery piping | Scupper pipes | 100% | | | | | | | | |
| Machinery piping | Bilge, ballast, FiFi | 50% | 50% | | | | | | | |
| Machinery piping | $CO_2$ | 100% | | | | | | | | |
| Machinery piping | Fuel | 100% | | | | | | | | |
| Machinery piping | Hot water | 50% | 50% | | | | | | | |
| Machinery piping | Cool water | 100% | | | | | | | | |
| Machinery piping | Fresh water | 45% | 55% | | | | | | | |
| Machinery piping | Sewage | 100% | | | | | | | | |
| Machinery piping | Sounding, filling & deaeration | 100% | | | | | | | | |
| Machinery piping | Lube oil | 100% | | | | | | | | |
| Machinery piping | Ventilation | 100% | | | | | | | | |
| Machinery piping | Ventilation ducts | 100% | | | | | | | | |
| Machinery piping | Exhaust gasses | 100% | | | | | | | | |
| Machinery piping | Cable transits | 100% | | | | | | | | |
| Machinery piping | Compressed air system | 100% | | | | | | | | |
| Machinery piping | Cargo & cleaning | 95% | 5% | | | | | | | |
| Electrical | Batteries | | 50% | | | 50% | | | | |
| Electrical | Electrical cables & wiring | | 100% | | | | | | | |
| Electrical | Switchboards | | 50% | | 50% | | | | | |
| Electrical | Hold lights | | | | 100% | | | | | |
| Bridge Equipment | Bridgewing & remote controls | 90% | | | 10% | | | | | |
| Bridge Equipment | Loading computer | | | | 100% | | | | | |
| Bridge Equipment | Navigation & communication equip. | | | | 100% | | | | | |
| Tools & spares | Tools & spares | 100% | | | | | | | | |
| Main engine | Main engine & flywheel | | | 100% | | | | | | |
| Shafts | Propeller shaft, flange, bearings, seals, caps & nuts | 100% | | | | | | | | |
| Propeller | Propeller blades & hub | | 100% | | | | | | | |
| Auxiliary engine[s] | Bow thruster E-motor | | | 100% | | | | | | |
| Auxiliary engine[s] | Auxiliary generator | | | 100% | | | | | | |
| Auxiliary engine[s] | Emergency generator | | | 100% | | | | | | |
| Auxiliary engine[s] | Shaft generator | | | 100% | | | | | | |
| Machinery components | Railings, stairs, ladders, platforms | 100% | | | | | | | | |
| Machinery components | Lashing rail | 100% | | | | | | | | |
| Machinery components | Gratings E.R. | 100% | | | | | | | | |
| Machinery components | Insulation E.R./tanktop | | | | | 100% | | | | |
| Machinery components | Inventory E.R. | 100% | | | | | | | | |

**Table B.2:** Transformation matrix #2

| Group | Item | Ferrous | Non-ferrous | Machinery | Electrical & electronic equip. | Minerals | Plastics | Liquids, chemicals & gasses | Joinery | Miscellaneous |
|---|---|---|---|---|---|---|---|---|---|---|
| Machinery equipment | Chassis/ mountings | 100% | | | | | | | | |
| Machinery equipment | Reduction gearbox | | | 100% | | | | | | |
| Machinery equipment | Couplings | 100% | | | | | | | | |
| Machinery equipment | Hydraulic system prop + casing | 85% | | 15% | | | | | | |
| Machinery equipment | Rudder including rudder stock | 100% | | | | | | | | |
| Machinery equipment | Ruddertrunk | 100% | | | | | | | | |
| Machinery equipment | Stearing gear installation | | | 100% | | | | | | |
| Machinery equipment | Bow thruster | | | 100% | | | | | | |
| Machinery equipment | Bilge, ballast, deckwash systems | | | 100% | | | | | | |
| Machinery equipment | $CO_2$ bottles | 100% | | | | | | | | |
| Machinery equipment | $CO_2$, watermist, sprinkler system | | | 100% | | | | | | |
| Machinery equipment | Loose FiFi equipment | | | 100% | | | | | | |
| Machinery equipment | Fuel oil system | | | 100% | | | | | | |
| Machinery equipment | Economizer | | | 100% | | | | | | |
| Machinery equipment | Cooling water system | | | 100% | | | | | | |
| Machinery equipment | Fresh & seawater system | | | 100% | | | | | | |
| Machinery equipment | Sewage system | | | 100% | | | | | | |
| Machinery equipment | Sounding, filling & deaeration system | | | 100% | | | | | | |
| Machinery equipment | Lubrication oil system | | | 100% | | | | | | |
| Machinery equipment | Natural & mechanical air system | | | 100% | | | | | | |
| Machinery equipment | Air conditioning system | | | 100% | | | | | | |
| Machinery equipment | Central heating system | | | 100% | | | | | | |
| Machinery equipment | Exhaust gas system | | | 100% | | | | | | |
| Machinery equipment | Incinerator plant | | | 100% | | | | | | |
| Machinery equipment | System fillings | | | 100% | | | | | | |
| Machinery equipment | Secondary systems | | | 100% | | | | | | |
| Machinery equipment | Emergency fuel stop actuators | | | 100% | | | | | | |
| Machinery equipment | Compressed air system | | | 100% | | | | | | |
| Machinery equipment | Cargo pumps, equipment & cleaning | | | 100% | | | | | | |
| Crane # | Store crane | | | 100% | | | | | | |
| Crane # | Cargo crane fore | | | 100% | | | | | | |
| Crane # | Cargo crane aft | | | 100% | | | | | | |
| Crane # | Adaptor fore | | | 100% | | | | | | |
| Crane # | Adaptor aft | | | 100% | | | | | | |
| Hatches | Foundations, hatches & small steel items | 100% | | | | | | | | |

**Table B.3:** Transformation matrix #3

| Group | Item | Ferrous | Non-ferrous | Machinery | Electrical & electronic equip. | Minerals | Plastics | Liquids, chemicals & gasses | Joinery | Miscellaneous |
|---|---|---|---|---|---|---|---|---|---|---|
| Outfitting fore | steel Outfitting | 100% | | | | | | | | |
| Outfitting fore | Anchor | 100% | | | | | | | | |
| Outfitting fore | Anchor chain | 100% | | | | | | | | |
| Outfitting fore | Chain stoppers | 100% | | | | | | | | |
| Outfitting fore | Anchor mooring winch | | | 100% | | | | | | |
| Outfitting fore | Pump units | | | 100% | | | | | | |
| Outfitting fore | E-anchor winch | | | 100% | | | | | | |
| Outfitting fore | Mooring winch | | | 100% | | | | | | |
| Outfitting fore | Tow & mooring lines, fairleads, chocks, etc. | 100% | | | | | | | | |
| Outfitting fore | Life boat, life raft, rescue boat | 25% | | | | | 75% | | | |
| Outfitting fore | Gangways | 100% | | | | | | | | |
| Outfitting fore | Inventory various | | | | | | | | 100% | |
| Outfitting mid | steel Outfitting | 100% | | | | | | | | |
| Outfitting mid | Fenders | 25% | | | | | 75% | | | |
| Outfitting mid | Pump units | | | 100% | | | | | | |
| Outfitting mid | Mooring winches | | | 100% | | | | | | |
| Outfitting mid | Tow & mooring lines, fairleads, chocks, etc. | 100% | | | | | | | | |
| Outfitting mid | Gangways | 100% | | | | | | | | |
| Outfitting mid | Inventory various | | | | | | | | 100% | |
| Outfitting aft | steel Outfitting | 100% | | | | | | | | |
| Outfitting aft | Anchor winch aft | | | 100% | | | | | | |
| Outfitting aft | Stern anchor | 100% | | | | | | | | |
| Outfitting aft | Pump units | | | 100% | | | | | | |
| Outfitting aft | Mooring winches | | | 100% | | | | | | |
| Outfitting aft | Tow & mooring lines, fairleads, chocks, etc. | 100% | | | | | | | | |
| Outfitting aft | Free fall boat | | | | | 20% | 80% | | | |
| Outfitting aft | Life boat, life raft, rescue boat | 25% | | | | | 75% | | | |
| Outfitting aft | Gangways | 100% | | | | | | | | |
| Outfitting aft | Floors, walls, ceilings | 20% | | | | | 30% | | 50% | |
| Outfitting aft | Sanitary | 25% | 5% | | | 20% | | | 50% | |
| Outfitting aft | Wheelhouse equipment | | | | 100% | | | | | |
| Outfitting aft | Furniture | | | | | | | | 100% | |
| Outfitting aft | Galley equipment | | | | | | | | 100% | |
| Outfitting aft | Inventory bosun store | | | | | | | | 100% | |
| Outfitting aft | Inventory various | | | | | | | | 100% | |
| Outfitting aft | Accommodation equipment | | | | | | | | 100% | |
| Paints & cathodes/anodes | Paint | | | | | | | | | 100% |
| Paints & cathodes/anodes | Cathodes/anodes | | 100% | | | | | | | |

**Table B.4:** Transformation matrix #4

| Group | Item | Ferrous | Non-ferrous | Machinery | Electrical & electronic equip. | Minerals | Plastics | Liquids, chemicals & gasses | Joinery | Miscellaneous |
|---|---|---|---|---|---|---|---|---|---|---|
| Forepeak Fcl | Foreship | 100% | | | | | | | | |
| Forepeak Fcl | Doors, manholes, bottom plugs, tween deck support, foundations, cable trays | 100% | | | | | | | | |
| Forepeak Fcl | Construction additions [bollards, lifting lugs, etc.] | 100% | | | | | | | | |
| Forepeak Fcl | Railings, stairs, ladders, platforms | 100% | | | | | | | | |
| Forepeak Fcl | Bowthruster tunnel | 100% | | | | | | | | |
| Forepeak Fcl | Masts fore | 100% | | | | | | | | |
| Forepeak Fcl | Bulbous bow | 100% | | | | | | | | |
| Cargo section | Midship, double bottoms, wingtanks | 100% | | | | | | | | |
| Cargo section | Crane foundation in hull | 100% | | | | | | | | |
| Cargo section | Winch & davit foundations | 100% | | | | | | | | |
| Cargo section | Auto & store crane foundation | 100% | | | | | | | | |
| Cargo section | Doors, manholes, bottom plugs, tween deck support, foundations, cable trays | 100% | | | | | | | | |
| Cargo section | Railings, stairs, ladders, platforms | 100% | | | | | | | | |
| Cargo section | Construction additions [bollards, lifting lugs, etc.] | 100% | | | | | | | | |
| Cargo section | Lashing rail | 100% | | | | | | | | |
| Machinery section | Aftship | 100% | | | | | | | | |
| Machinery section | Winch & davit foundations | 100% | | | | | | | | |
| Machinery section | Auto & store crane foundation | 100% | | | | | | | | |
| Machinery section | Engine & gearbox foundation | 100% | | | | | | | | |
| Machinery section | Doors, manholes, bottom plugs, tween deck support, foundations, cable trays | 100% | | | | | | | | |
| Machinery section | Construction additions [bollards, lifting lugs, etc.] | 100% | | | | | | | | |
| Machinery section | Lashing eyes, bollards, bulkhead fittings | 100% | | | | | | | | |
| Machinery section | Masts aft | 100% | | | | | | | | |

**Table B.5:** Transformation matrix #5

| Group | Item | Ferrous | Non-ferrous | Machinery | Electrical & electronic equip. | Minerals | Plastics | Liquids, chemicals & gasses | Joinery | Miscellaneous |
|---|---|---|---|---|---|---|---|---|---|---|
| Casing funnel | Funnel | 100% | | | | | | | | |
| Accommodation | Accommodation | 80% | | | | | | | 20% | |
| Crane pedestal[s] | Crane pedestal[s] | 100% | | | | | | | | |
| Deck house | Deck house | 100% | | | | | | | | |
| Liquids | All "contents" | | | | | | | 100% | | |
| Tol & margin | Tol & margin | 100% | | | | | | | | |

# C

# Sustainable Value Stream Maps

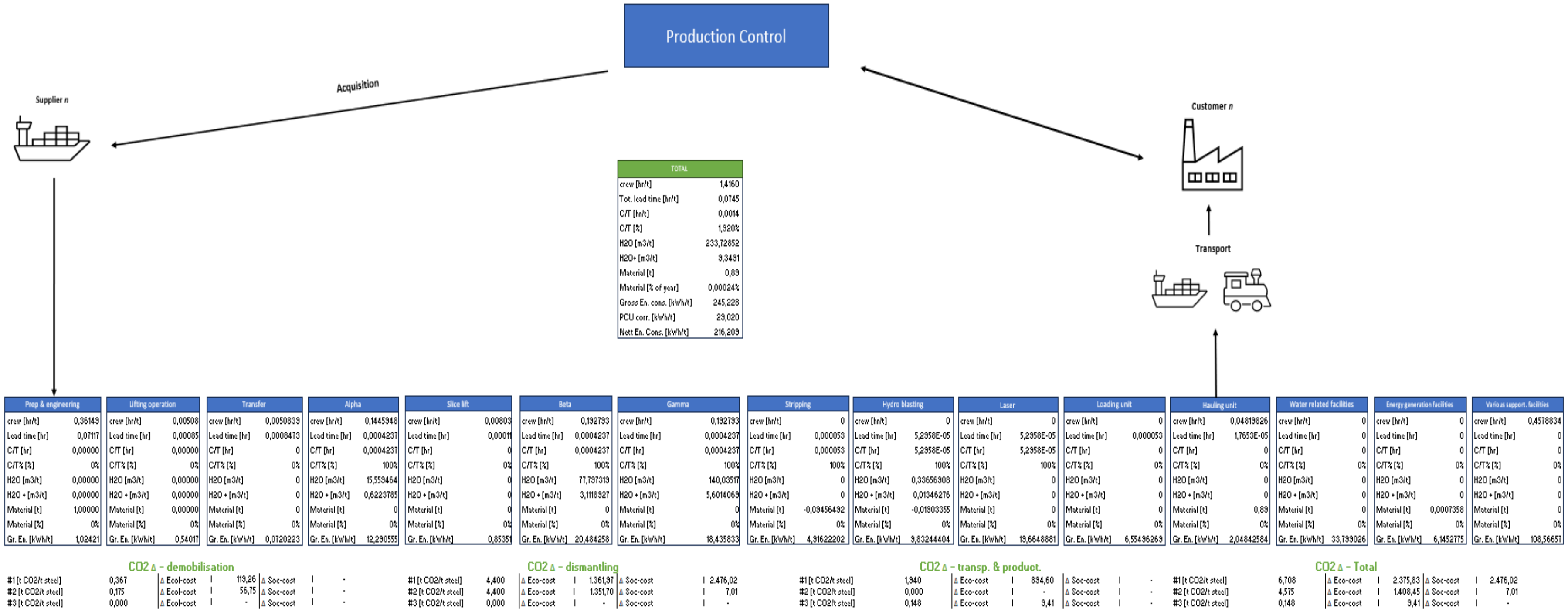


**Figure C.1:** SVSM map - container ship

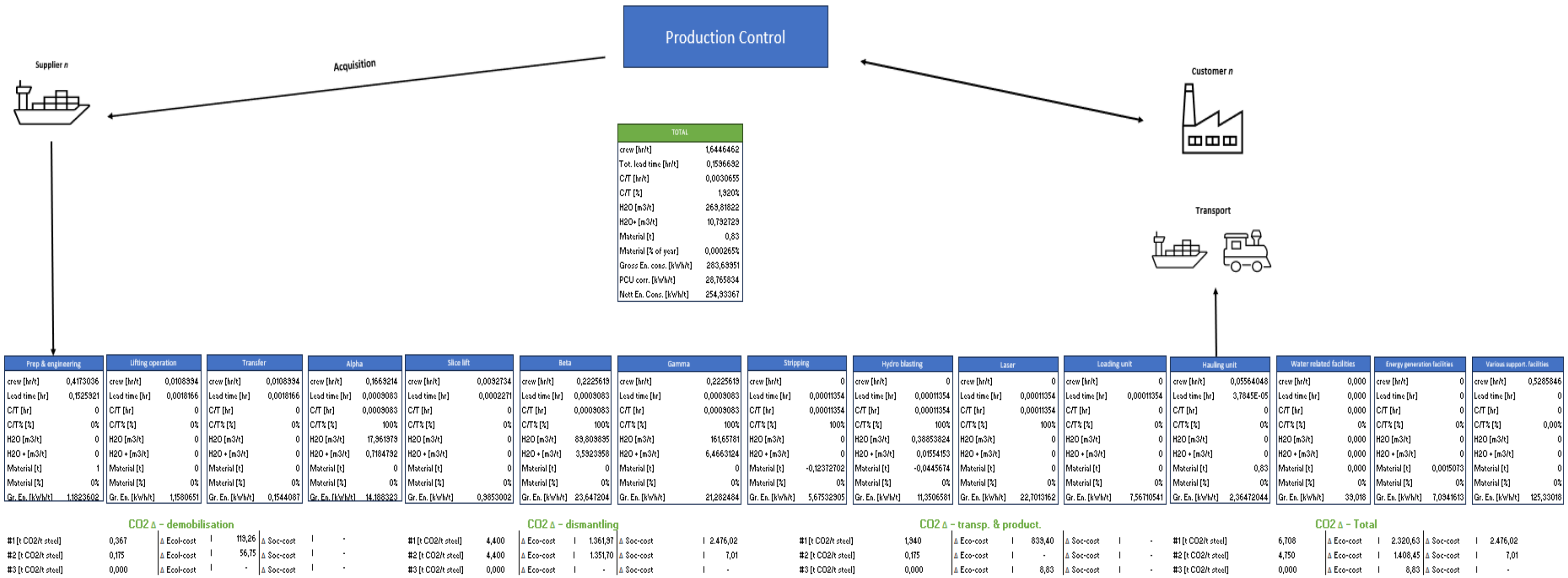


**Figure C.2:** SVSM map - Product tanker

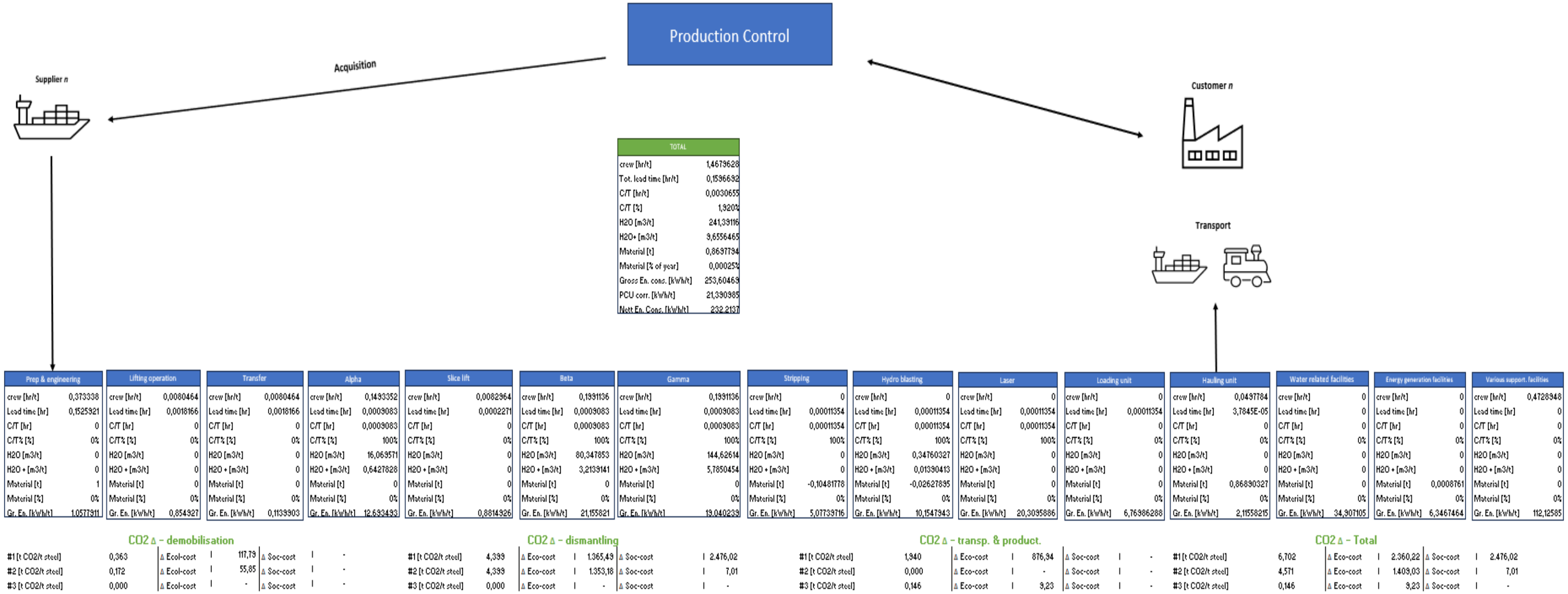


**Figure C.3:** SVSM map - MPP vessel

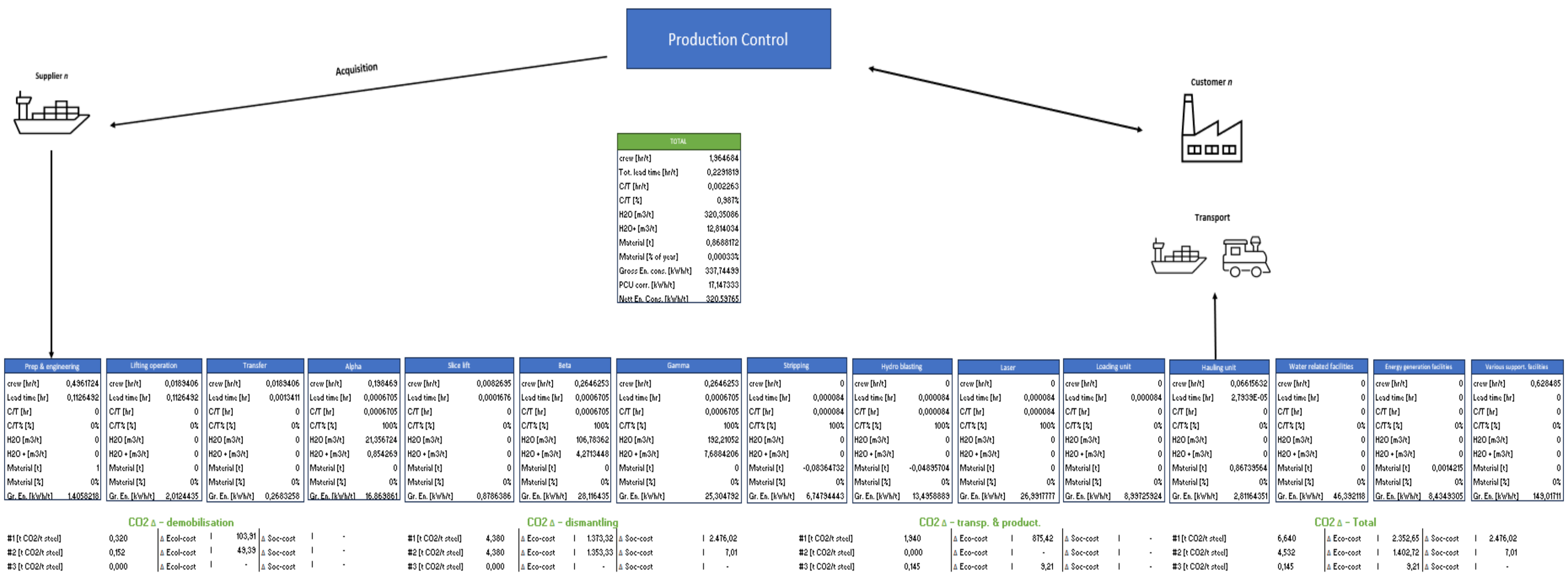


**Figure C.4:** SVSM map - GC vessel